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TUNGSTEN DEPOSITS OF THE DARWIN HILLS, INYO COUNTY, CALIFORNIA.

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ABSTRACT.

Exploitation of tungsten orebodies in a silver-lead district has revealed new data, in conflict with published accounts of Darwin ore genesis. Knopf's assignment in 1913 of pyrometasomatic origin was contested by Kelley, who, in 1937, suggested mesothermal classification. A high-temperature formation of scheelite is indicated by its intimate association with wollastonite and marks the earliest epoch of metallization. Mineralization is channeled by fractures into receptive sediments, and forms replacement lodes. Veins, faults, and fissures, first mapped by Kelley and analyzed by their frequency and magnitude of occurrence, are defined as systems forming a pattern of tear lines and tension fractures. Regional continuity of the former supports a concept of tectonic development rather than local origin confined to the influence of the Darwin intrusive.

The extensive development of scheelite ore shoots since discovery in 1940 maintains a reserve approximating 25,000 tons, with other estimates of available ore varying to 70,000 tons. The study and analysis of ore foci suggests potential reserves of several hundred thousand tons, which warrants substantiation in order to justify installation of a mill within the district. The latter will eliminate current tendency toward selective mining which results in loss of greater potential production of vital metal.

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INTRODUCTION.

UNDER the stimulation of wartime demands, the exploitation of Inyo County's tungsten deposits in the northern part of the county [2] placed California first in domestic production of concentrates, and intensified prospecting in neighboring districts. By the end of 1940 a high-grade body of scheelite ore had been discovered 100 miles southeast of the Sierra Nevada ores in the Darwin Hills,[3] a district credited with a production of approximately $5,000,000 from silver-lead ores. The discovery was followed early in 1941 by the acquisition of 23 mining claims by the E. L. Cord interests and in the ensuing twelve months, which included the entry of the United States into World War II, had been exploited by the construction of surfaced roads, power lines, the opening of the deposits by more than 6,000 feet of development work, and an attained production of 30,940 tons of ore. The grade of ore milled approximates one per cent of WO_3.

The entry of the Darwin tungsten deposits into the list of important new producers has permitted a renewal of geologic studies which began with Knopf's [4] brief examination of the silver-lead ores in 1913. No strictly geological reports appeared thereafter until the publication of Kelley's reports [5] in 1937 and 1938 which

[2] Lemmon, D. M.: Tungsten deposits in the Sierra Nevada near Bishop, Calif. U. S. Geol. Surv. Bull. 931–E, 1941.

[3] Discovered by Curley Fletcher. Geologists who have scouted the arid region of the southwest may recall his popular campfire ballad, "The Strawberry Roan."

[4] Knopf, Adolph: The Darwin silver-lead mining district, Calif. U. S. Geol. Surv. Bull. 580–A, 1913.

[5] Kelley, V. C.: Origin of the Darwin silver-lead deposits. ECON. GEOL., 32: 987–1108, 1937; and Geology and ore deposits of the Darwin mining district, Calif. Jour. Mines and Geol., 34: Oct., 1938.

noted the presence of scheelite in the "gangue mineralization" of the silver-lead deposits. Attention was first directed to tungsten ores in particular in 1941 by Lemmon's examination for the U. S. Geological Survey,[6] and studies have continued by geologists of the Cord interests to the present.

REGIONAL SETTING.

The Darwin Hills are situated 100 miles southeast of Bishop and 230 miles northeast of Los Angeles. The town of Darwin on the western slope of the hills is easily reached by State Highway 190 between Lone Pine in Owens Valley, and Death Valley National Monument (Fig. 1). Owens Valley lies between the

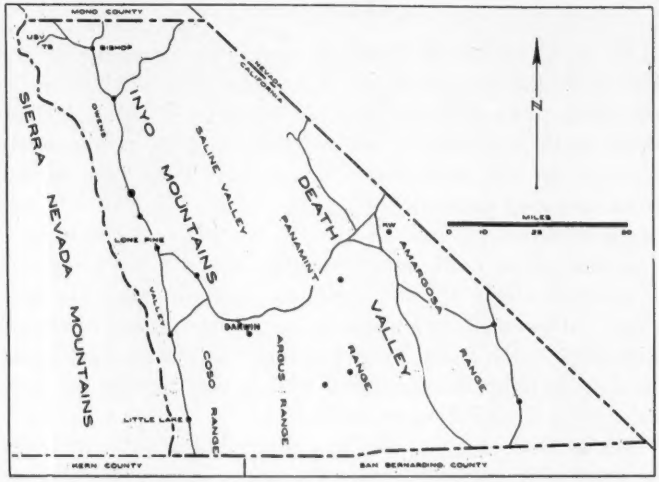

FIG. 1. Inyo County, California. *USV*, U. S. Vanadium Corp.; *TS*, Tungstar Mine; *KW*, Keane Wonder Mine.

eastern escarpment of the Sierra Nevadas and the steep western front of the Inyo-White mountains. The latter is a crustal block originally raised in the early development of Mesozoic orogeny

[6] Report unpublished.

and finally emboldened by faulting, folding, and intrusion during the growth of the Great Basin province.[7] Physiographically, the southwesterly trend of the Inyo range is broken into detached segments which remain exposed above a broad plateau. This plateau has preserved the older land forms of truncated folds and surrounds the smaller Darwin Hills more recently elevated above its surface. The Coso Range borders the plateau to the west and together they effect a partial closure of Owens Valley. To the east lies the Argus Range; and then is resumed the easterly progression of present Great Basin land forms—the depressions of Saline and Panamint Valleys, the elevation of Panamint Range, the great depression of Death Valley, and so on.

GENERAL GEOLOGY.

Rocks. The Darwin Hills rise moderately above the general level of the plateau for a length of six miles and a width of one to two miles. The rocks include a variable series of Paleozoic limestones which have been arched anticlinal along the northwesterly trend of the hills, and subsequently invaded by a long, narrow stock composed essentially of quartz diorite (Fig. 2). The age of the limestones has been identified by Knopf[4] as Pennsylvanian. The strata strike northwesterly roughly parallel to the elongation of the stock which, in turn, parallels the anticlinal axis of the sediments. The anticline simulates the easterly thrust pattern of fold alignments in the Basin Range province,[8] the eastern flank being buckled into tight, almost isoclinal folds, in contrast with the regular westerly dips of the opposite flank.

The invasion of quartz diorite was largely guided by the older structure of the Pennsylvanian limestones. Some evidence of pre-intrusive fracturing is displayed east and northeast of Darwin townsite where moderate warps in the anticlinal axis have been broken westerly along closely spaced shears and subsequently in-

[7] Knopf, Adolph: Geologic reconnaissance of the Inyo Range. U. S. Geol. Surv. Prof. Pap. 110, 1918.

[8] Billingsley, Paul and Locke, A.: Structure of ore districts in the continental framework. A. I. M. E. Trans., vol. 144, 1941.

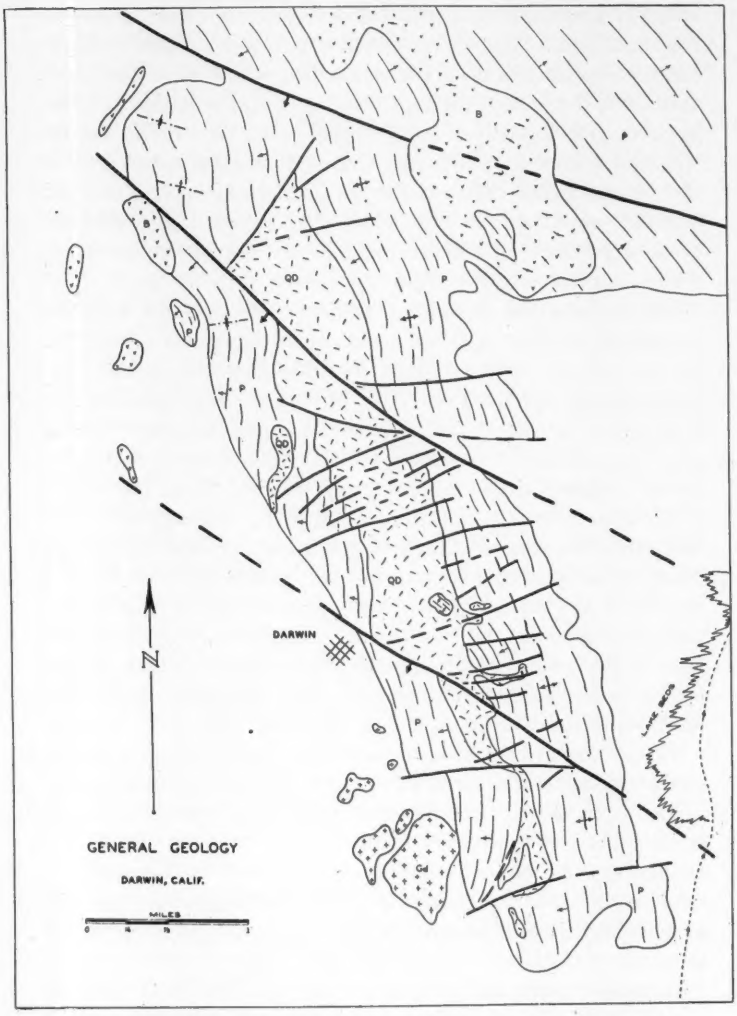

FIG. 2. General geology of the Darwin Hills. P, Pennsylvanian hornfels and limestones; QD, Quartz diorite; B, Basalt cap; Gd, Granodiorite.

vaded by fingers of the quartz diorite. Bedding plane slippage on the west flank of the rising anticline probably assisted emplacement. The stock is generally concordant with the beds which lie farthest to the west of the anticlinal axis, but is prominently transgressive as it approaches the crumpled crest. It extends the full length of the Darwin Hills attaining its maximum exposed thickness in the higher relief of the north-central area, and thinning southerly with the reduced relief of the southern end of the hills. Shallow pendants of altered limestone are not uncommon along the eastern and northern edges of the stock.

The initial effect of folding and intrusion was the early development of metamorphosed rocks consisting mainly of hornfels and wollastonite-tactite, derived from the pure and impure limestone members of the Pennsylvanian series. The term hornfels is here broadly used to define the dense, somewhat cherty-looking rock recrystallized from impure beds. The name wollastonite-tactite is applied to the more extensive silicate rocks; unprefixed, tactite here refers to the members displaying characteristic "contact" minerals such as garnet, idocrase, and infrequently epidote. Many of the purer limestone members, where unbroken and not transected by fracture, retain their original texture without appreciable alteration, and by their easy recognition serve as marker-beds in the mapping of ore-bearing structures. Where accompanied by adequate ore channelways, they also serve as principal host to important tungsten-bearing solutions.

The tactites are not always confined to the immediate environs of the exposed stock, nor is there any consistency in areal pattern of the depth of recrystallization of silicate rocks away from the stock. There is however, a marked affinity between tactites and fracturing. In the area of tungsten deposition southeast of the stock, tactites occur prominently where both large and small elements of the Darwin fracture system transect the purer calcareous beds.

It appears that an analysis of the effect of the stock on rock alteration should emphasize the phases of magmatic emanations which evidently preceded and accompanied ore mineralization.

The escape of substances from the invading melt may have produced early recrystallization; but the subsequent consolidation of the magma was followed by patterned fracturing which provided new avenues of escape for agents contained in the still fluid interior of the intrusive. Thus guided by more closely confined channelways, alteration became more selective, choosing the horizons of easier accessibility. Then the transition of fractures to a semblance of veins was effected by the deposition within them of persisting mineralized solutions. Sufficient mineralizers were contained to effect metallization of the permeable horizons by introduction of iron, tungsten, silver and lead, and in lesser quantities zinc and copper.

Metasomatic replacement of confined horizons, displayed in Darwin as areas contiguous to fractures which are both local and continuous, along and across bedding planes, was thus facilitated and developed the conspicuous idocrase-garnet zones. The absence of the later ore minerals in some of the altered zones indicates that not all of these metasomatic centers were kept open. In general, however, as in the silver-lead bodies to the northwest and the concentration of tungsten to the south, the tactites remained permeable, and thus receptive, by rejuvenation of fracturing along the previously determined lines of weakness. Permeability was probably augmented by mineral fracture.

In brief, consideration of the field evidence to define the processes of rock alteration indicates two distinct stages of metamorphism: the earlier recrystallization of invaded rocks, and a later selective metasomatism, channeled by fractures, which created the host of ore deposition.

Fracture Systems. The structure pattern of the ore district is shown in Figure 3. Two major fracture systems form a pattern of northwesterly tear lines intersected by steep, northeast fissures. Only the latter have proved productive. Three principal tears cut the hills—one crosses the northern end, a second flanks the north slope of Ophir Peak (tangential to synclinal drag folds), and a third borders the small basin due east of the town of Darwin. The northernmost shear was first recognized in 1937 by Kelley

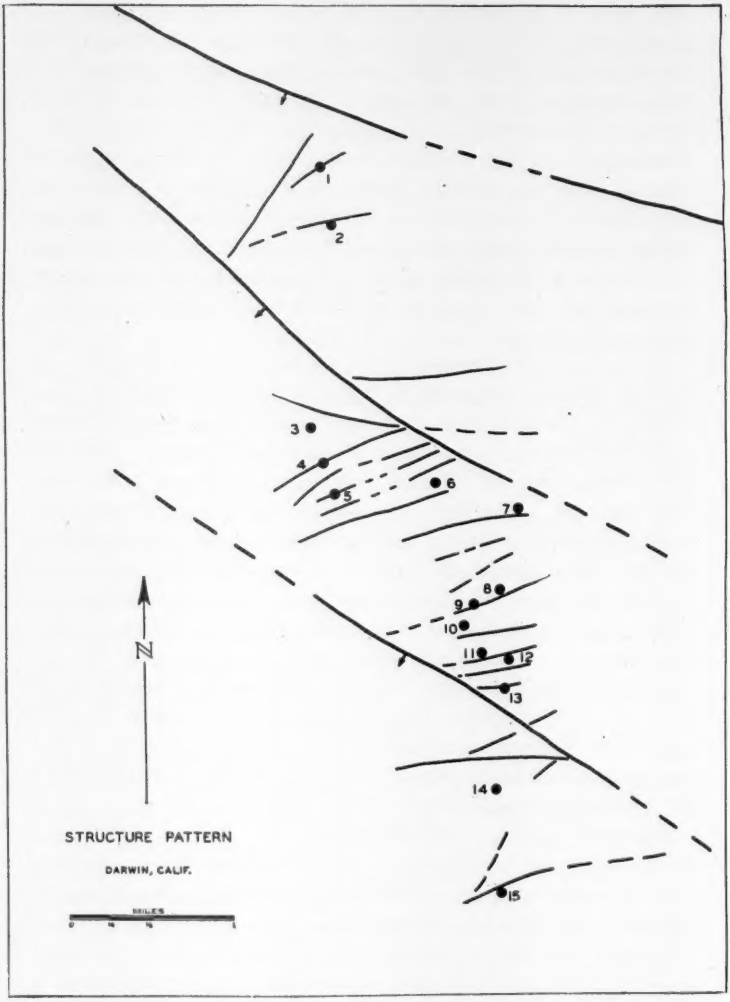

FIG. 3. Tear fault and fissure pattern. Heavy lines northwest, tear faults; heavy lines northeast, fissures . . . MINES: 1. Lucky Jim, 2. Christ-

and Hopper [9] who reported "a considerable component of [normal] displacement," in addition to horizontal motion which moved the north side westward. This probably results from stresses produced by east-west compression during lateral folding of the sediments. The shear zone can be traced westerly beyond the hills into remnant folds of the plateau and easterly to the adjacent Argus Range. Topographic expression suggests an unbroken trace westward, through the property of Sierra Talc Company and across the south end of Inyo Range to Owens Lake. Since the fault is evidently an element of the structure pattern, its continuity precludes any concept of development of the system by the Darwin intrusive. The central and southern tear lines in effect frame the currently productive portion of the district: between them lie the lead ores of the Thompson, Defiance, and Independence group of mines, and the tungsten ores of the Durham, Fernando, and St. Charles. The northernmost and central tears enclose the earlier-minded lead and silver ore of the Lucky Jim and Christmas Gift mines (Fig. 3).

Further ground failure as a result of stretching between the tear lines developed tension fractures represented by the northeast system. Shorter or discontinuous elements of the latter form gash veins. A notable example is the Lucky Jim vein, credited with an estimated silver-lead production of $2,000,000.

Other faults and fissures include bedding plane fractures which are important in ore localization. Local expressions of these bedding slips suggest their early development, probably accompanying the primary folding of the Darwin anticline under compression from the west and east. Intersecting sets of small fractures or joints east of the stock strike parallel to the anticlinal axis and to bedding but diverge in dip below the anticline. In the St. Charles mine, on the 130 foot level, motion on the northeast fracture near the anticlinal axis has produced strong slips and striae

[9] Op. cit., p. 519.

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mas Gift, 3. Independence, 4. Thompson, 5. Defiance, 6. National Tungsten, 7. Lane, 8. Custer, 9. St. Charles, 10. Alameda, 11. Fernando, 12. Durham, 13. Chipmonk, 14. Promontory, 15. Silver Reef.

which dip 47° E. Good exposures of compressional joints are observed in cross section in the Durham mine.

Largest fault displacements, compounded by recurrent motion, occur on the tear lines. Readjustments during mineralization are common on productive fractures, and they attain final post-ore expression in slight displacements distributed northwesterly, particularly on the northeast system. In general, the end-stage of fracturing post-dates consolidation of the intrusive.

SCHEELITE OREBODIES.

Mineralogy. The tungsten ore consists of the calcium tungstate, scheelite, variably distributed in a gangue of lime silicates which include wollastonite, grossularite garnet, and idocrase (Fig. 4).

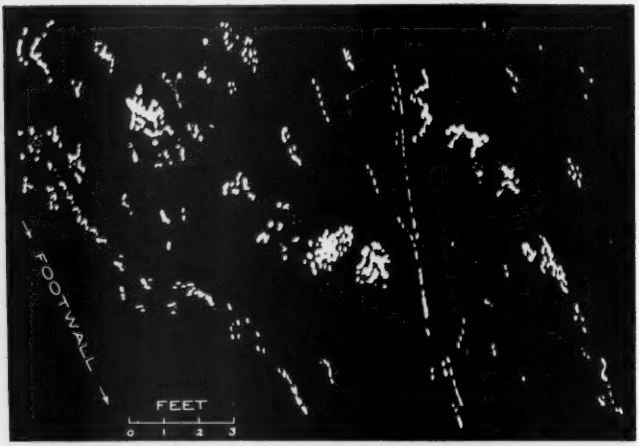

FIG. 4. Distribution of high-grade scheelite as shown by ultra-violet light. Durham vein, panel No. 206.

Scheelite occurs frequently in euhedral crystals up to one half inch in diameter, particularly in the Fernando and Hayward "glory holes." Other gangue minerals include calcite, often in large cleavable masses, chalcedony, and occasionally fluorite.

Pyrite is profuse and its oxidation to limonite (and hematite) permeates the gangue extensively, thereby accentuating ore horizons. The lighter rusty browns of these channeled oxides is readily distinguished from the disseminated pyritization of the country rock that stains the crumpled beds of the Darwin anticline and its environs. Though predominantly transported, limonite is abundant in the form of pseudomorphs after pyrite.

An interesting association of bismuth and barite with scheelite ore occurs in the Fernando mine near the junction of Fernando fissures with the Durham limestone. Bismuth with silicon is locally a major constituent of the ore under the spectrograph, with tungsten, calcium, and iron intermediate. The bismuth occurs as the sulphide bismuthinite coated with fibrous, greenish bismutite (a basic bismuth carbonate), and included galena which is probably argentiferous in view of recognition of silver in the spectrum only (also see below). Barite is found in adjacent parts of the same orebody as small veinlets through shattered grains of scheelite in a gangue of idocrase, garnet, and wollastonite. The barium solutions apparently replace some of the lime minerals.

In the St. Charles canyon east of Darwin townsite, ore samples from the small Hayward "glory hole" show quartz, feldspar, epidote, and a little granular titanite (calcium titanium silicate) with some sphalerite. Occasional occurrence of chrysocolla and chalcocite derived from small quantities of primary chalcopyrite is observed in the Alameda shaft and lower levels of the Durham mine. Linarite, a basic sulphate of lead and copper, also is found associated with tungsten ore in the Alameda Lime Belt (Fig. 6) and, more conspicuously, in the lead mines of Imperial Metals Company.

Origin and Classification. Scheelite is found with argentiferous galena and lead carbonates in the north-central part of the district but in the high-grade tungsten orebodies of the southeastern portion silver-lead minerals are uncommon. This relative paucity of scheelite in the lead ores and, conversely, of lead in the principal tungsten deposits, raises a question of mineral zoning which does not appear to be satisfactorily demonstrated. The

known orebodies of each of the metals are contained in like elements of the controlling fracture system, but when in similar proximity to the intrusive they occur on opposite sides of the stock. In this setting, scheelite deposition shows preference for the under, or eastern side of the stock in the sheared beds which flank the Darwin anticline. Some of the fractures on the east side have been exploited for lead ore with only minor success; commercial orebodies generally were farther east of present tungsten deposits.

The approximate paragenesis of principal minerals appears to be wollastonite, idocrase, grossularite-garnet, scheelite, pyrite, and galena. Pyrite deposition apparently continued throughout ore concentration and is not necessarily a "mineral guide." (Its profuse occurrence had occasioned some speculation in Darwin on its being a guide to scheelite deposits in garnetized areas.) Microscopic examination of tungsten ore from the Durham mine showed development of scheelite and the lime silicates was practically contemporaneous. In the Fernando mine the impure galena, bismuthinite, and possibly native bismuth form finely-divided particles attached to larger grains of scheelite and quartz. Also of interest is Lemmon's report [10] of the occurrence of euhedral scheelite encrusted with cerusite in the Imperial lead mines to the northwest.

The inference is that scheelite deposition accompanied the formation of the high temperature silicates and was succeeded by the deposition of silver-bearing galena, and lesser quantities of sphalerite, bismuth, and barite in a decreasing temperature gradient, with fissures serving as the ore conduits. It is suggested that if these factors be used to attempt classification (using the widely adopted genetic scheme of Lindgren) there may ensue a confusion of pyrometasomatic features (synonymous with contact-metamorphic), and the high to moderate temperatures of hypothermal and mesothermal deposition. The two published opinions on the origin of Darwin ore deposits are somewhat at variance. While more conclusive evidence continues to be made available, and in the light of important scheelite concentrations, the writer

[10] Oral communication.

suggests that Knopf's [4] concept of sequence in time with decreasing temperatures be accepted, qualified by emphasis of structural controls. Kelley's [5] objection appears to be mainly one of conflict in pointed classification, which is admittedly an elastic and somewhat difficult undertaking. However, his conclusion that all of the ore deposition took place "during a single short period under nearly constant temperature conditions" of mesothermal environment is not wholly applicable. The intimate association of scheelite with the lime silicates, in particular wollastonite which is known to form above 600° C.,[11] shows that a high degree of heat prevailed at the onset of metallization. Similarly in Darwin, the established occurrence of galena as a successor to wollastonite would preclude any confinement of temperatures within the accepted gradient of mesothermal ore deposition.

The writer believes that the channeled mineralization is punctuated by stages, or epochs of metallization, the first of which is defined by the high temperature formation of scheelite. In terms of general classification, the deposits should be considered contact-metamorphic only in the sense of proximity to metasomatic centers, with due regard for the structural controls of "ground preparation" and deposition of ore under variable conditions of temperature. These factors can be more adequately assigned to replacement lodes.

Localization of Ore Shoots. Tungsten orebodies, and evidently those of silver-lead, are directly related to the Darwin fracture system. Economically, fractures of the northeast tension group are of most significance as broader guides to ore structure. The shear zones of the northwest tear lines have not been proved commercial though mineralization is not entirely absent.

Scheelite orebodies are formed at structural clusters where elements of the fracture system transect variable combinations of bedding planes and slips, brecciated beds, and purer belts of altered limestone. None occur inside the main body of the stock and, in addition, a given mineralized cross fissure will localize shoots

[11] Bateman, A. M.: Economic Mineral Deposits. John Wiley and Sons, New York, 1942. P. 82.

of ore only when metal deposition is facilitated by entry of the fissure into these prepared horizons. Thus the relative permeability of bed structure defines the ore reservoir. For example, the ore shoot of the Durham mine lies in a bedding plane slip on the contact between hornfels and crystalline blue limestone. The fracture was apparently derived from slippage attending uplift of the Darwin anticline, with late readjustments on the plane evidenced by footwall gouge and striae which obliterate cross shears. Multiple components of the Fernando shear zone intersect the bed structure and intensify scheelite concentration in direct proportion to the magnitude of shearing (Fig. 5). Where the cross frac-

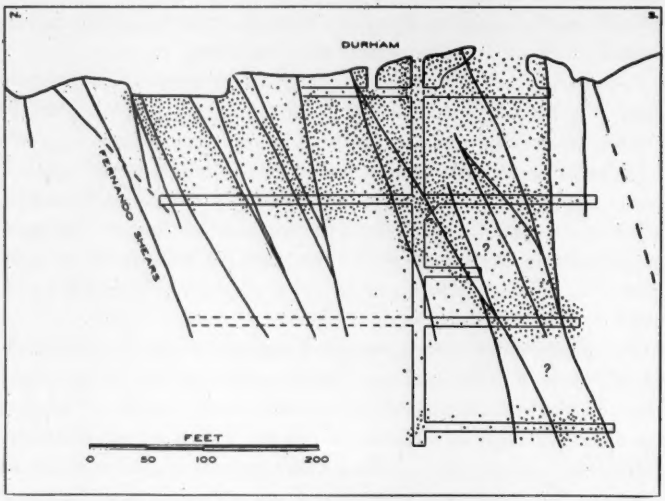

FIG. 5. Intensity of scheelite mineralization (dotted) in Durham ore shoot. Looking east.

tures leave the Durham limestone for the finer grain of hornfels, diminution of scheelite content results; where they re-enter the parallel belts of Frisco and Alameda limestones, ore reservoirs again develop (Fig. 6). The high tenor of ore in the St. Charles mine, where alteration has masked the crystalline limestone, is

dependent upon a local hanging wall brecciation which concentrated ore against the impermeable footwall of sheared hornfels. Scheelite is dispersed when the shear passes west into compact hornfels until receptive bedding planes are reached where the ore host again expands (Fig. 7). Similarly to the east, parallel shears of the St. Charles zone combine with bed structure flanking the Darwin anticline to produce the ores of the Custer mine.

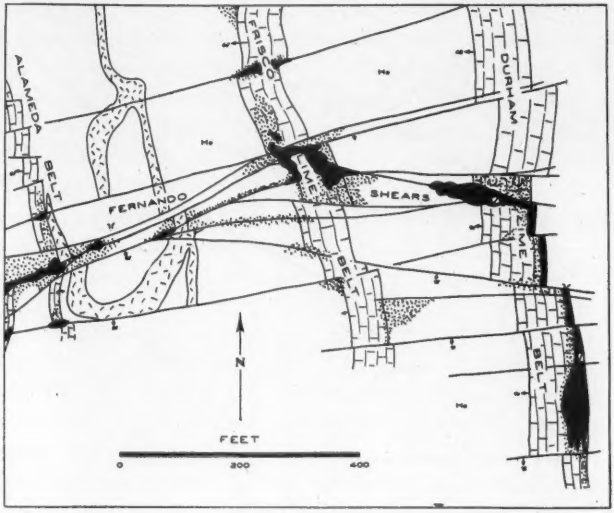

FIG. 6. Localization of ore bodies (black) in parallel limestones. *Ho,* hornfels; *dotted,* tactite; *hatched,* quartz diorite.

Orebodies do not always outcrop, and the absence of commercial values in a surface exposure of ore structure does not preclude deeper enrichment. The deposit in the Alameda mine is found commercial at a depth of 95 feet; the Durham ore shoot which is continuous on the 100 level for over 300 feet outcrops in shorter "runs" of ore.

Size and Grade of Tungsten Ore. During the first twelve months following discovery (1941 into 1942), it is estimated that

production from leasers, prospectors, and the properties of the Cord interests approximated 32,000 tons of tungsten ore averaging more than one per cent WO_3. The Durham, Fernando, and St. Charles mines are the most productive in the district; the ore shoots in these mines alone furnish over 95 per cent of the total ore mined. The width of the average scheelite ore mined varies

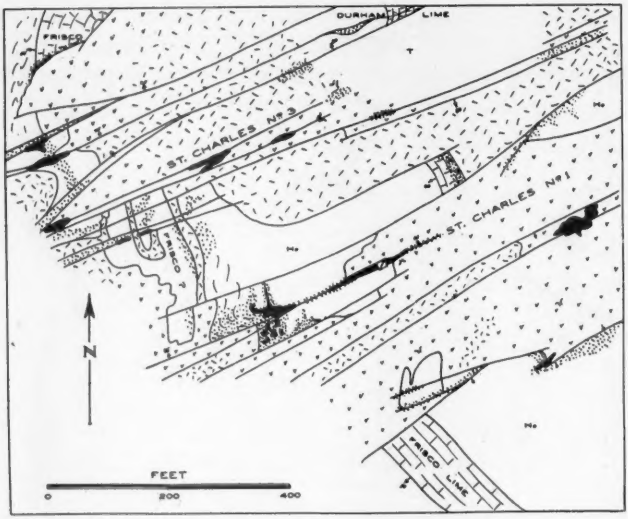

FIG. 7. Scheelite ore (black) in St. Charles shear zone. *Ho*, hornfels; *dotted*, tactite; *hatched*, quartz diorite; *checked*, hybrid diorite-and-hornfels; *T*, talus.

from two feet to a maximum of 35 feet, the latter width attained in the south orebody of the Durham mine. Here the ore shoot has been mined 14 feet wide from a depth of 125 feet to the surface for a length of 60 feet. On the 200 and 300 foot levels below these stopes development headings have indicated that the length of the shoot approximates 80 feet and that commercial widths will average 15 feet of about one per cent ore, with local swells in sheeted ground reaching a 35 foot maximum. The

spread of ore along the Durham fissure on the 100 level extends a continuous length of 350 feet. Lateral development of this structure on the lower levels is designed to exploit inferred continuity in depth. The ore shoot of the St. Charles mine averages 2 to 3 feet in width but the smaller tonnage available is compensated by high tenor of ore; samples of mined ore frequently contain 5 to 7 per cent of WO_3.

Depth of Ore Expectancy. The confinement of orebodies to the rocks and structure of the sediments suggests that many of the northeast fissures served as trunk channels, or principal conduits. The *end stage* of controlling structure, that which encloses minable orebodies, is generally obvious to even the casual observer, and its continuity on lower mine levels can be assumed the preliminary guide to additional ore. However, an identification of the *primary* channels which guided ore minerals to final deposition is believed to be the key to possibilities of ore in depth. For example, the question arises: do tension fractures connect the roots of scheelite mineralization with the final ore host enclosed in bed structures, thus imposing a relatively shallow limit on the latter? The evidence is not sufficiently factual, but it is hoped that continued studies will permit segregation of the primary and final conduits. Meanwhile, it is suggested that in the shoots of scheelite ore, the *depth zone of ore expectancy* be assumed dependent upon the persistency of enclosing structures.

FUTURE OF TUNGSTEN MINING IN THE DISTRICT.

Estimates of tungsten ore available from current development made in behalf of Metals Reserve Company, have varied from 40,000 to 70,000 tons of ore containing 0.60 per cent of WO_3. More conservative estimates by the principal operators establish a reserve of 26,000 tons available to present facilities for milling. The development program will delimit further the known ore shoots in the Durham, Fernando, Alameda, and many other mines of the district; tonnage will be increased by activities of National Tungsten Company and by accessory production from lead-ore treatment at Imperial Metals, Inc. But it is believed no less im-

portant to intensify exploration of potential orebodies. Characteristic mineral and structural sequences discussed in the preceding pages, emphasize the latent possibilities for ore in the Frisco and Alameda Lime Belts, the Chipmonk, St. Charles No. 3, and Silver Reef prospects. Implied tonnage of this nature is difficult to appraise; only a test of selected ore clusters can permit a legitimate estimate. Costly exploration will often be found necessary but should give favorable results when guided by competent geologic advice.

The future of tungsten mining will be governed by the ultimate objective of development and exploration: a substantiation of geologically-inferred orebodies which would permit greater production than now possible. A treatment plant located within the district can reduce present high costs of ore transportation to the Keeler mill (operated by West Coast Tungsten Company twenty miles distant). High costs in turn promote selective mining; orebodies impoverished for large-scale mining result, and a greater potential production of vital metal is lost. The stimulus of wartime prices and the premium allowed on over-quota production will encourage private initiative to reach this objective.

ACKNOWLEDGMENT.

The author wishes to express his appreciation to Pacific Tungsten Company and to Mr. A. N. Sweet, General Manager of the Cord Interests, for permission to publish this article.

DARWIN, CALIFORNIA,
April 21, 1943.

THE ALKALI SULPHIDE THEORY OF GOLD DEPOSITION.[1]

F. GORDON SMITH.[2]

ABSTRACT.

Making certain geological and chemical assumptions, it is postulated that the natural solutions which deposit primary gold ores contain alkali sulphide, and that the gold is transported as alkali thioaurite. It is shown experimentally that gold is soluble in, and can be crystallized from, such solutions. Two other common gold minerals, *electrum* (Au, Ag) and *calaverite* ($AuTe_2$), can be similarly synthesized. Other associated features, such as wall-rock alteration and associated minerals, are shown to be compatible with the primary postulate.

INTRODUCTION.

THE literature on the theory of formation of ore deposits is abundant considering the difficulty of scientific observation of the process in nature, and in recent years there has been a tendency for the various theories to agree on certain fundamentals. It is thus unnecessary to recall the history of this interesting subject; only the assumptions on which the following theory of gold deposition is based will be described.

The experimental method adopted was to use available facts and reasonable assumptions to postulate how gold is transported and deposited in primary gold deposits. Following this, a series of laboratory experiments were performed in order to test the chemical possibilities. In this way, a general type of process is postulated that permits gathering field evidence by which the theory can be tested. This type of reasoning is useful in theoretical phases of ore genesis due to the difficulty of direct observation of the natural processes and the difficulty of duplicating the postulated processes in the laboratory.

1 Published by permission of the National Research Council of Canada.

2 Research Laboratory, International Nickel Company of Canada, Limited, Copper Cliff, Ontario.

DEVELOPMENT OF THE THEORY.

It is commonly believed that during the late stages of cooling, consolidation and crystallization-differentiation of large igneous intrusives, residual solutions become increasingly rich in all of the components present in small amounts. Thus water and most of the components of metalliferous veins are progressively concentrated in the residual solutions, which are finally expelled from the magma chamber into major and minor openings in the rocks overlying the cooling intrusives. Deposition of the components of the ore-bearing solutions is believed to take place in a successive manner due to falling temperature and pressure, and also due to reaction with the rocks through which the solutions pass. The physical representation of such ore-bearing solutions has been postulated to be the hot springs which issue on the earth's surface in regions of recent vulcanism.

It is believed by many authorities that most igneous ore deposits are formed at depths where pressures are too great to allow the separate existence of a vapor phase in contact with a liquid phase, and also that critical conditions may never be reached during the crystallization of a magma (Morey, 1924). In addition, there appears to be no fundamental reason for differentiating between fluid solutions, one of which would expand indefinitely with no separation into two phases, and one which would pass through a stage where two fluid phases exist, one a liquid and the other a gas (see Hannay and Hogarth, 1879–82). That is, the character of a fluid solution is determined by the temperature, pressure and dissolved components and not by whether it is technically a gas or liquid solution. The primary assumption will thus be made that the aqueous solutions, formed in the magma after the majority of the silicates have crystallized, are in equilibrium with the silicates with which they are in contact, and no assumption need be made as to what would happen to the solutions if the pressure changed.

Very little is known about the system—solid silicates-aqueous solutions of silicates—at high temperatures, but there is apparently no theoretical basis for believing that it is very different

qualitatively from this system at normal temperatures. Provided this is so, silicates will be in equilibrium with a solution which contains their components, though in different proportions. Day and Allen (1924) have stated it in this manner:

> . . . if liquid water arises directly from the magma it is impossible to understand how the water could ever be anything but alkaline, for the hydrolysis of the alkali silicates bringing soluble hydroxides into the liquid phase of the system would preponderate over acid-forming reactions on account of the much greater quantities of alkali than acid elements like sulfur and the halogens in every igneous rock.

In addition, because of the strong ionizing power of the alkali metals, the ratio of the concentration of alkali metal ions to ions containing say aluminum and silicon will be greater in the aqueous solutions than in the silicates with which they are in contact. Thus the aqueous solutions will be strongly alkaline in the ordinary use of the term (Graton, 1940, p. 207). The course of crystallization of a magma under normal conditions is believed to be a continuous process with falling temperature such that the fluid phase becomes richer in water and certain other components as crystallization of silicates takes place (Morey, 1924). This aqueous extract is expelled from the magma chamber in part by forces which represent the continuation of forces which injected the primary magma and in part by increasing pressure of the aqueous fraction as non-volatile constituents such as silicates are precipitated.

The alkali solutions derived from the fractional crystallization of a silicate magma contain those constituents of the magma which dissolve more readily in the solution than they form orthomagmatic minerals. They deposit sulphides and sulpho-salts of the metallic elements, carbonates of the alkali earths, and silica, as well as minor amounts of selenides, tellurides, arsenides, oxides, sulphates and native metals, so that the solutions leaving the magma chamber must of necessity contain these constituents. Although the character of aqueous solutions at elevated temperatures in equilibrium with both alkali silicates and metallic sulphides is not known, it is reasonably certain that alkali sulphides

must be present, since among the many reactions possible the following appears to take place (Foreman, 1929):

$$MS + NaOH \rightleftharpoons MO + NaHS$$

The sulphide concentration must be large enough to force this equilibrium far enough to the left that metallic sulphides are stable, since the solutions deposit sulphides and are stable in contact with them, except in the regions of high temperature, where some oxide deposition can occur (*e.g.* cassiterite, magnetite, and hematite). The excess alkali sulphide may form soluble sulphides with the metallic sulphides, driving the following equilibrium to the right (Becker, 1887, 1888; Ogryzlo, 1935):

$$MS + 2xNaHS \rightleftharpoons MS.xNa_2S + xH_2S.$$

Thus if aqueous solutions are in equilibrium with both alkali silicates and metallic sulphides, they will contain alkali ion, complex silicate ions, complex metallic sulphide ions, and all the minor ionic types in equilibrium with these, such as sulphide, hydrosulphide, and hydroxide. Deposition of dissolved silicates may be due, among other things, to a decrease in the hydroxide ion concentration brought about by change of temperature (and to a minor extent pressure) and by a change in the relative amounts of the components due to reaction with the wall-rock. Deposition of the metallic sulphides may be due to the decrease in the sulphide ion concentration brought about by similar factors.

Having thus postulated that igneous ore-deposition solutions are hot, aqueous and alkaline, there remains a demonstration that the elements found in ore deposits of igneous origin are soluble together in such solutions and that the minerals found in the deposits can be synthesized by laboratory processes which duplicate, as closely as possible, the postulated conditions. Since the theory is being applied specifically to gold deposits, the chemical experiments will deal only with the gold minerals.

SOLUBILITY OF GOLD IN ALKALI SULPHIDE SOLUTIONS.

Eggleston (1880), performing experiments to throw some light on the formation of gold nuggets in nature, showed that

spongy gold is dissolved by solutions of alkali sulphide. This was confirmed by Liversidge (1893).

In explaining the solution and deposition of cinnabar, G. F. Becker (1887, 1888) showed how cinnabar is reversibly soluble in solutions of sodium sulphide. He applied the results of his chemical experiments to explain the natural transport of mercury, and this theory at the present day appears to be the one most widely accepted for mercury deposition. Becker also reported that gold is present in some California districts which contain mercury, and from this association he "concluded that gold should be soluble in sodium sulphide." Simple experiments showed that gold is very soluble in solutions of sodium sulphide. Becker reported that at ordinary temperature and pressure, 843 parts of sodium sulphide (Na_2S) by weight dissolved one part of gold. Gold was also shown to be soluble in sodium hydrogen sulphide and in solutions of sodium carbonate partly saturated with hydrogen sulphide. The solubility of gold in these solutions was said to be increased and facilitated by an increase in temperature.

Important contributions to the chemistry of gold were made by Victor Lenher. He determined some of the chemical properties of gold and attempted to relate these to the natural solution and deposition of gold. In his first paper (1912) he pointed out that double salts of gold and alkali metals are easy to prepare and some of them are more stable in contact with reducing agents than are auric chloride and aurous chloride. The most stable double compounds are the complex sulphides with alkali metals. Such double sulphides are soluble in water and gold is not precipitated from the aqueous solutions by pyrite or metallic iron, but is precipitated when the double sulphide is decomposed by oxidation or by the addition of acid. Lenher concluded "that of the various means of solution and transportation of gold which have been observed, it would appear that the alkaline sulphide solution may with study solve some at least of the problems of gold deposition."

J. W. Gruner (1933) discussed the earlier work on the solubility of metallic sulphides in alkali sulphide solutions. His few

experiments showed that metallic gold is not soluble in sodium sulphide solutions at elevated temperatures, whether alone or in the presence of quartz. This was interpreted to mean that hot alkali sulphide solutions do not play an important role as carriers of gold in nature.

S. P. Ogryzlo (1935) studied some of the properties of gold in systems including sodium sulphide. He reported that solutions of sodium sulphide and polysulphide dissolve only traces of gold at high temperatures and pressures, but that solutions of sodium hydrosulphide dissolve considerable quantities of gold both at high temperatures and pressures and at normal temperature and pressure. He concluded that in alkaline solutions gold may be carried as a double sulphide of an alkaline metal and gold: precipitation is brought about through oxidation or acidification.

J. L. Lindner and J. W. Gruner (1939), studying the effect of alkali sulphide solutions on common minerals, reported some of their solutions dissolved and reprecipitated the gold lining of the bomb. Aqueous solutions of sodium sulphide and hydrogen sulphide alone apparently did not dissolve gold but it was freely soluble in solutions of sodium hydrosulphide, and in a few cases was deposited on the altered mineral sections.

Recently Zviagincev and co-workers have performed a number of experiments which tend to confirm the earlier results. Zviagincev and Paulsen (1940) studied the solubility of gold in solutions of sodium and potassium sulphide and hydrosulphide. They reported that the solubility of gold depends on the concentration of the alkali sulphide, and that it increases very greatly with increased temperature. Metallic sulphides and quartz do not precipitate gold from such solutions. From these facts they postulated that gold deposits are formed from solutions of gold in alkali sulphide, precipitated by fall in temperature. The natural association of gold and certain sulphides was regarded as merely fortuitous.

The solubility of gold in alkali sulphide solutions has been variously reported. The problem can be approached in two ways: either the loss in weight of metallic gold kept in contact with

alkali sulphide solutions can be measured, or double sulphides of gold and alkali metal can be prepared and their solubility in water can be determined. Experiments of the former type have been carried out, as described, by Gruner (1933), Ogryzlo (1935), Lindner and Gruner (1939), and Zviagincev and Paulsen (1940). There is general agreement that gold is soluble in solutions of NaHS (aqueous solutions of $Na_2S.9H_2O$ saturated with H_2S at room temperature and pressure), only slightly soluble in solutions of Na_2S (aqueous solutions of $Na_2H.9H_2O$), and almost insoluble in solutions of Na_2S_x (sulphur dissolved in aqueous solutions of $Na_2S.9H_2O$). Ogryzlo reported that only traces of gold were dissolved by solutions of sodium sulphide at temperatures from 175° to 300° C. However, in solutions of sodium hydrosulphide he reported that from room temperature up to 300° C. gold was dissolved and remained in the solutions after cooling. His data indicate that solubility increases with increasing temperature, and Zviagincev and Paulsen (1940) confirmed this, although the temperature range of their experiments was from 15° to 80° C. Neither of these papers proves that the amount of gold reported dissolved represents completely saturated solutions. It appears more likely that the very sluggish nature of the dissolution of metallic gold in sodium hydrosulphide solutions is influencing the results, and that the greater the concentration of alkali sulphide and the higher the temperature, the more rapid the solution. This is apparent from the data, since the reported amount of dissolved gold is that left in the solution *after cooling*. If the data indicate true solubility, then all the experiments should show the same amount of gold dissolved, and this should be the same as the amount dissolved at *room temperature*. Ogryzlo (1935) also studied the solubility of gold in sodium polysulphide solutions at 300° C. He reported only traces of gold in the solutions after cooling, but as he pointed out (p. 423), the solutions when placed in the bomb were yellow, but after heating and cooling they were colorless, indicating that the polysulphide complex ion was destroyed by some chemical change. Thus the reported solubility of gold in sodium polysulphide solutions of a stated concentration is

in reality the solubility in the solutions that remain after heating and cooling. The compositions of these were not determined.

Gold sulphides (Au_2S, Au_2S_2, Au_2S_3) are soluble in solutions of sodium sulphide, polysulphide, and hydrosulphide (Mellor, 1923, pp. 610–614). The solubility of gold sulphide depends upon its method of preparation, on the temperature of the solutions, and on the length of time in contact with the solutions, and reliable data on its solubility seem to be lacking. No difficulty was ever found in dissolving gold sulphide in solutions of sodium sulphide, polysulphide, or hydrosulphide in the experiments which follow, and the amount which dissolves is considerable.

The state of the gold in auriferous solutions of sodium sulphide has been studied by Yorke (1849), Ditte (1895 and 1907) and Antony and Lucchesi (1889, 1890, 1891 and 1896). Yorke and Ditte prepared the compounds $Na_2S.Au_2S$ and $K_2S.Au_2S$ either by dissolving the fusion of gold and sodium polysulphide in water or by dissolving gold sulphide in aqueous solutions of sodium sulphide. The sodium compound crystallized with 8 molecules of water according to Yorke and 10 molecules of water according to Ditte. The crystals were apparently monoclinic and very soluble in water. The analogous potassium salt crystallized with water, but the exact amount was not determined. Ditte formed the compound $2Na_2S.Au_2S$ by dissolving gold sulphide in sodium hydrosulphide and reported that it crystallized with 20 molecules of water. Antony and Lucchesi formed the crystalline compounds $3Na_2S.Au_2S$ and $3K_2S.Au_2S$. Ditte prepared the compound $4K_2S.Au_2S$ by dissolving gold sulphide in a small excess of potassium sulphide. The compound crystallized with 12 molecules of water and was very soluble in water, giving a yellow solution. It is noteworthy that the only stable double sulphides of gold and alkali metals mentioned by Mellor (1923) are those in which the gold is monovalent (Au_2S), though Antony and Lucchesi reported an unstable compound, $3Na_2S.Au_2S_3$. Thus in all probability gold is dissolved by alkali sulphide solutions with the formation of thioaurites of various complexities. These form hydrated crystals which are very soluble in water. The maximum

concentration of gold in a sodium sulphide solution of definite concentration may then be determined by the amount of gold contained in a solution of sodium thioaurite. It is thus apparent that, neglecting hydrolysis effects, the concentration of gold in alkali sulphide solutions must vary directly with the concentration of alkali sulphide.

The relation of the solubility of gold sulphide to the solubility of other metallic sulphides in alkali sulphide solutions is of importance in explaining the paragenesis of gold ores, since as a first approximation, metals more soluble would be expected to be precipitated in nature after metals less soluble in such solutions. All of the common metals and their sulphides are soluble in melts of sodium sulphide or polysulphide forming double sulphides (Freeman, 1925; Steck, Slavin, and Ralston, 1929; Friedrich; Smith, 1939). In fact, sodium sulphide is exceedingly corrosive, forming double sulphides with the metals in a manner somewhat analogous to the formation of double oxides of sodium and the alkali earths and semi-metals (aluminates, silicates, etc.). The much greater solubility of metallic sulphides in melts of sodium sulphide than in aqueous solutions of sodium sulphide may be explained by the fact that the sulphide concentration of such melts is greater than that possible in aqueous solutions where oxygen, taking the place of sulphur, lowers the sulphide ion concentration. Therefore, when double sulphides formed by fusion are dissolved in water, the complex is usually broken down with solution of the sodium sulphide and precipitation of the metallic sulphide. In the case of mercury, antimony, arsenic, tin, molybdenum, and gold, the double sulphides are soluble in water and form true solutions (Freeman, 1925; Becker, 1888; Gruner, 1933; Smith, 1939).

From a study of the solubility of various metallic sulphides in solutions of sodium sulphide (Smith, 1939), it was concluded that they fall into three groups:

(*a*) sulphides which are not very soluble in melts of sodium polysulphide;

(*b*) sulphides which are very soluble in melts of sodium polysulphide, but insoluble in aqueous solutions of sodium polysulphide at ordinary temperatures;

(*c*) sulphides which are very soluble in melts of sodium polysulphide and also very soluble in aqueous solutions of sodium polysulphide.

Included in group (*a*) were molybdenum disulphide (MoS_2, molybdenite), and ferrous disulphide (FeS_2, pyrite). Included in group (*b*) were zinc sulphide (ZnS, sphalerite), lead sulphide (PbS, galena), cuprous sulphide (Cu_2S, chalcocite), silver sulphide (Ag_2S, argentite), ferrous sulphide (FeS, pyrrhotite), cadmium sulphide (CdS, greenockite) and bismuth sulphide (Bi_2S_3, bismuthinite). Included in group (*c*) were mercury sulphide (HgS, cinnabar), arsenic monosulphide (AsS, realgar), antimony sulphide (Sb_2S_3, stibnite), and molybdenum sulphide. In group (*b*) it was found that silver sulphide is more soluble than the sulphides of zinc, lead, and copper. It was also subsequently found that bismuth sulphide may be placed in group (*c*), since it is slightly soluble in concentrated solutions of sodium sulphide. According to the data collected by Mellor (1931, pp. 113–4), tellurium sulphide is very soluble in aqueous solutions of alkali sulphide. Thus the common metallic sulphides most soluble in alkali sulphide solutions, which we have deduced to be carriers of gold in nature, include the sulphides of gold, tellurium, mercury, arsenic, antimony, bismuth and silver. Minerals containing a similar association of metals have frequently been reported to have been deposited late in the ore sequence in several gold ore deposits.

CRYSTALLIZATION OF GOLD, ELECTRUM, AND CALAVERITE.

As described previously, aqueous solutions of gold and sodium sulphide, hydrosulphide, and polysulphide are quite stable if kept away from the action of air. If left to oxidize, they do so slowly, the soluble sulphides forming sulphates and thiosulphates. In addition, they absorb carbon dioxide which displaces hydrogen sulphide from the soluble sulphides. At room temperature, solutions of gold in dilute sodium hydrosulphide deposit a dark brown or black precipitate of gold sulphide, but in moderately concen-

trated solutions, a light brown precipitate of metallic gold is formed. On the steam bath uncovered solutions deposit a bright yellow crystalline precipitate of metallic gold. During their study of the sulphides of gold, Antony and Lucchesi found that gold sulphide could only be precipitated in aqueous solutions if the temperature was below 40° C.

Another method of decomposing the double sulphide of gold and sodium is to allow Allen's reaction [8] to proceed to completion. An experiment was carried out by the writer several years ago which forms an example of this very general method of mineral synthesis. Gold, sodium sulphide and sulphur were fused together, dissolved in water, and 10 cc. of the resultant solution filtered into a pyrex test tube of 20 cc. capacity. The open tube was placed vertically inside an iron screw-top bomb, and a small amount of water was placed in the bottom of the bomb. The inside surface of the bomb was covered with a thick coating of rust, which subsequently served as a hydrogen sulphide absorbent. The bomb was sealed and heated to 330° C. for 12 hours and then allowed to cool. On opening, the solution in the tube was found to be colorless and nearly clear, and its volume was about 10 per cent less than when placed in the bomb. A deposit of crystalline metallic gold had formed around the inside of the tube about 1 cm. above the level of the solution and around the upper end of the tube, and some was also present half way down the outside of the tube. A deposit of crystalline gold could be seen in the bottom of the tube underneath the solution. The inside surface of the glass tube had been decomposed to an opal-like material and this alteration could be seen irregularly disposed on the outside of the tube for a short distance from the top. The iron oxide covering the inside surface of the bomb had been partly converted into pyrrhotite and pyrite. No smell of hydrogen sulphide was noticed when the bomb was opened. Apparently the solution expanded on heating to the point where some spilled over the top of the

[8] A general reaction whereby free sulphur is converted to sulphide and sulphate ions by water. In systems including alkali polysulphide, the chief products are hydrogen sulphide and sodium sulphate.

tube, and at that time some gold must have been in solution. Subsequently the internal reaction must have taken place (Allen's reaction) which lowered the sulphide concentration and liberated hydrogen sulphide, which was then adsorbed by the iron oxide. As the reaction proceeded, crystals of gold were precipitated.

The crystals formed during the above experiment were too small to determine their habit, but in a similar experiment which was carried out in an attempt to prepare the gold telluride (calaverite, $AuTe_2$) large crystals of gold were formed. In this experiment a solution was prepared containing 0.5259 gram of gold, 0.3400 gram of tellurium, 0.5985 gram of sulphur, 3.4620 grams of $Na_2S.9H_2O$, and enough water to make the total volume up to 12 cc. The solution was placed in an open pyrex tube, the total capacity of which was 20 cc. The tube was placed vertically inside a graphite-lined steel bomb (Smith, 1939). The space around the tube was filled with crushed fine-grained goethite together with a little water. The total empty space was about 20 cc., the air in which was displaced by hydrogen sulphide immediately before sealing the bomb. The bomb was heated to 250° $\pm$ 10° C. in three hours, kept at this temperature for four hours, and then allowed to cool slowly to room temperature, which took about 18 hours. When the bomb was opened, there was only a slight smell of hydrogen sulphide. The solution was still yellow, however, and its volume was about 15 per cent greater than when put into the bomb. Crystals of gold (and a few of tellurium) were seen in clusters lining the inside of the glass tube in contact with the solution and also for a short distance (about 0.5 cm.) above its surface. The inside of the tube in contact with the solution and for a short distance above it had been altered to a white, translucent material. The iron oxide surrounding the tube had been partly converted into a black fine-grained mixture of iron sulphides. The gold was in two forms: dendritic aggregates of small crystals, and thin platy crystals with hexagonal outlines and perfect mirror-like surfaces. The maximum size of the latter crystals was about 3 mm. across the plate. Both forms of native gold have been frequently described (Dana, 1914, p. 15).

Native gold is generally alloyed with some silver, which varies from traces to slightly over 50 atomic per cent (Dana, 1914, p. 15). The term *electrum* is generally applied to argentiferous gold if the silver content is about 20 per cent by weight (approximately 31 atomic per cent silver). In order to demonstrate that the crystallization of electrum can be carried out in solutions which we are here postulating to be the natural carriers of the metals, an experiment was performed in which the sulphide concentration was reduced in a system which included gold, silver, and sodium sulphide.

A 3 M. solution of $Na_2S.9H_2O$ was saturated with hydrogen sulphide, and 25 cc. of the resultant solution placed in a graphite-lined steel bomb (Smith, 1939). The internal volume of the bomb was approximately 50 cc. Freshly precipitated Au_2S_2 (0.4308 gm.) and Ag_2S (0.2327 gm.), corresponding to an equal atomic ratio of gold and silver, were added to the solution. The air over the solution was displaced with hydrogen sulphide gas, the graphite lid was placed on top of the graphite lining, and a layer of precipitated ferric hydroxide was placed over the top of the graphite lid to keep the hydrogen sulphide gas from attacking the gasket of the bomb. This had the further effect of adsorbing hydrogen sulphide and thus assisted in lowering the sulphide concentration of the solution. The bomb was heated to approximately 300° C. and then allowed to cool to room temperature in about 12 hours. No smell of hydrogen sulphide was noticed on opening the bomb. The solution was grayish green in color and slightly turbid. A fragment of siderite placed in the solution, had been replaced by a fine-grained black aggregate on which could be seen small, confused aggregates composed of yellowish-white metallic substance which proved to be electrum. The fine-grained black material, which was approximately the same shape as the original fragment of siderite, contained no gold but a little silver. It was composed chiefly of a mixture of pyrrhotite and pyrite, and in the center it contained a little unreplaced iron carbonate. The iron hydroxide which had been placed above the

graphite lid over the solution had been partly converted into a mixture of pyrite and pyrrhotite.

The sequence of events during heating and cooling is postulated to be as follows. The gold sulphide dissolved in the solution of sodium hydrosulphide immediately, and, on heating, the silver sulphide also dissolved. The sodium sulphide attacked the iron carbonate, producing iron sulphide, and the carbon dioxide dissolved in the solution. In addition, the hydrogen sulphide gas above the solution was slowly absorbed by the ferric hydroxide with which it was in contact. Both of these actions lowered the sulphide concentration of the solution until the point was reached where the double sulphides of gold and silver with sodium were decomposed, liberating the free metals which crystallized together. Most of the aggregates of electrum were isolated from the other solid phases by leaching with hydrochloric acid. They had a very pale yellow color with a high metallic luster, and were very malleable. This material was analyzed by dissolving in *aqua regia,* displacing the nitric acid with hydrochloric acid, dissolving the gold chloride, and leaving the silver chloride which was then weighed. The amount of silver was found to be 28 per cent by weight (approximately 42 atomic per cent). There was no assurance that each group of the electrum crystals had the same composition, but no color difference could be seen. Some silver was included with the mixture of iron sulphides, in a form not determined.

The result of this experiment was interpreted to mean that alkali sulphide solutions containing gold and silver will deposit metallic gold containing some silver when the sulphide concentration is reduced. It is of interest in this connection that by a somewhat similar method, metallic silver and copper can be crystallized from solutions of sodium polysulphide and hydrosulphide (Smith, 1939), but in this case the two metals crystallize side by side and do not form an alloy. Also where native copper and silver have been deposited together in ore deposits such as on Keweenaw Point in Lake Superior, they appear to crystallize independently.

Among the naturally-occurring gold tellurides only calaverite

($AuTe_2$) appears to be of such a nature that it can occur essentially free from silver. Some doubt has been expressed as to whether this mineral is a definite compound of gold and tellurium. Brauner (1889) believed that calaverite is a polytelluride which dissociates on heating, liberating tellurium, and leaving the compound Au_2Te. Lenher (1902) concluded that the tellurides of gold are not definite compounds but are alloys (solid solutions) of gold and tellurium, because several experiments showed that natural telluride minerals are capable of reducing gold chloride in aqueous solutions, and all attempts up to that time to prepare the pure telluride of gold ($AuTe_2$) had been unsuccessful. The methods used included the action of hydrogen telluride on dilute solutions of gold chloride, and the reduction of gold chloride and tellurium chloride solutions with sulphur dioxide. In the former case, metallic gold was formed and in the latter, gold was precipitated first, followed by tellurium. The compound $AuTe_2$ was obtained by Rose (1908) in the study of the alloys of gold and tellurium; this appeared to be identical with the natural mineral calaverite. The system Au–Te has been studied by Pélabon (1909, pp. 564–6) and by Pellini and Quercigh (1910). The results indicated that only one compound was formed, $AuTe_2$, which crystallized in simple eutectics with both tellurium and gold and apparently did not form solid solutions. Mellor (1931, p. 48) stated that because of the failure of the synthesis of calaverite by wet methods "it is inferred that the minerals have been formed by fusion processes." However, attempts at synthesis by wet methods have involved the use of gold chloride, which is probably not present in natural ore-bearing solutions.

The solubility of tellurium in alkali sulphide solutions depends upon several conditions. Tellurium can be dissolved in concentrated solutions of sodium sulphide, but the amount dissolved is rather small if the solutions have free access to atmospheric oxygen. Such solutions are deep red in color, and probably contain polytelluride complexes analogous to the polysulphides. Much more tellurium can be dissolved in solutions of sodium polysulphide, and these solutions are deep yellow in color. If a solution

of sodium sulphide is heated with tellurium, the solution aquires a faint reddish color, but when sulphur is added, this color is destroyed and a yellow compound forms on the fragments of tellurium. This rapidly dissolves in the solution. If enough sulphur is added, all of the tellurium can be dissolved, and highly concentrated tellurium solutions obtained. Provided these reactions are reversible, if the sulphur concentration of such a solution is slowly reduced, the soluble tellurium compound (probably a sodium thiotellurite—Mellor, 1931, pp. 113–4) is broken down, liberating tellurium which first forms a soluble polytelluride, and after saturation precipitates as free tellurium. When solutions of sodium thiotellurite are either acidified or slowly oxidized in contact with air, tellurium is precipitated. It was concluded that tellurium may be grouped with the metals whose sulphides are very soluble in alkali sulphide solutions, and since gold is also in this group, tellurium should show some relation to gold in time of deposition from the natural ore-bearing solutions. Such a relation is well known. Telluride minerals are commonly deposited late in the ore sequence, closely associated with gold. In addition, native tellurium has been reported as a very late mineral to be deposited (Watanabe, 1936).

Gold telluride ($AuTe_2$) has never been successfully synthesized by wet methods, but if it could be prepared in aqueous solutions, which we have postulated to be the carriers of ores in nature, the theory of the nature of such solutions would be greatly strengthened. The following experiments were undertaken in an attempt to prepare crystals of gold telluride.

Solutions of sodium thioaurite and sodium thiotellurite in many proportions and concentrations were mixed and no precipitation occurred. Such mixed solutions can also be saturated with hydrogen sulphide with no apparent change. Thus it appears that when tellurium is in the thiotellurite complex, it is "masked" and cannot unite with gold.

A mixed solution of sodium thioaurite and sodium thiotellurite was prepared such that the atomic proportions of gold and tellurium were equal. There was a slight excess of sodium poly-

sulphide present. The sodium concentration of the solution was approximately 1 N. At room temperature, the solution was fractionally precipitated with small additions of hydrochloric acid followed by filtration. In this way five lots of precipitate were obtained which represented all the gold and tellurium present in the solution. Each precipitate fraction was analyzed qualitatively and found to contain both gold and tellurium. Estimates of the amounts of each present showed that gold was greatest in the first, and least in the last fraction. An *x*-ray powder diffraction pattern of the first precipitate showed the presence of crystalline gold but not calaverite.

A solution of approximately the same constitution and concentration as described above was prepared, placed in a beaker, and covered with a watch-glass. The solution remained stable for about 8 days, but during the next 4 days a yellowish-brown crystalline precipitate of metallic gold separated and settled to the bottom of the solution. After the gold had precipitated, the solution underwent no apparent change for about 3 days, and then small, interlocking, dendritic, gray crystallites with a silvery metallic luster—apparently tellurium—began to form on the surface. This continued until the solution was clear and colorless and contained neither gold nor tellurium. Some of the gray crystalline material on top of the solution was tested for gold: none was found. Apparently the sodium gold sulpho-compound is broken down by atmospheric oxidation more readily than the sodium tellurium sulpho-compound, and if tellurium is present in the latter complex while the gold complex is being broken down, gold precipitates alone.

An experiment at an elevated temperature was performed in which the sulphur concentration was reduced by the operation of Allen's reaction. The conditions of this experiment have been described previously. The crystalline solids formed were metallic gold and tellurium, and from an examination of the crystals it was found that the gold crystallized first. The solution at the end of the experiment still contained some tellurium. A search was made under a high-power binocular microscope for crystals of

calaverite, but none were found. Apparently when the free sulphur concentration is high, and the gold and tellurium are both in the form of soluble thio-compounds, the operation of Allen's reaction, which lowers the sulphide concentration and decreases the alkalinity, breaks down the gold complex before the tellurium complex.

Failure to make calaverite by the simultaneous or successive break-down of soluble sodium thio-compounds of gold and tellurium necessitated other methods of synthesis. It was thought that if the sulphur concentration was low enough, tellurium might form the polytelluride instead of the thiotellurite ion. Thus in systems including thioaurite complexes, isomorphous replacement of sulphur by tellurium might take place, and if gold telluride is distinctly less soluble than gold sulphide, it would precipitate out of the mixed solution. In order to test this, a fusion of sodium polysulphide was prepared in which the free sulphur concentration was just great enough to allow fusion to take place at about 400° C. To this was added gold and tellurium in equal atomic ratio, until on cooling, two phases appeared. The cold fusion when broken showed an aggregate of purplish-brown crystals which contained sodium, sulphur, gold and tellurium. In addition, there was a very pale yellow substance with a metallic luster, in globular bodies. This contained gold and tellurium and was examined by the *x*-ray powder diffraction method. The resultant film was clear and sharp (Fig. 1). Comparison of the interatomic spacings corresponding to every measurable line, and their relative intensities with published spacings and intensities of powder diffraction patterns of calaverite ($AuTe_2$), krennerite ($(Au, Ag)Te_2$), and sylvanite ($AuAgTe_4$), showed that all the spacings given by Harcourt (1942) for calaverite were present, and in addition three which were listed for krennerite and sylvanite. These, however, were similar to, but slightly larger than, the spacings corresponding to the three strongest lines for gold. It was concluded that the substance made in the above experiment is a compound of gold and tellurium, and is probably very much like the natural mineral calaverite.

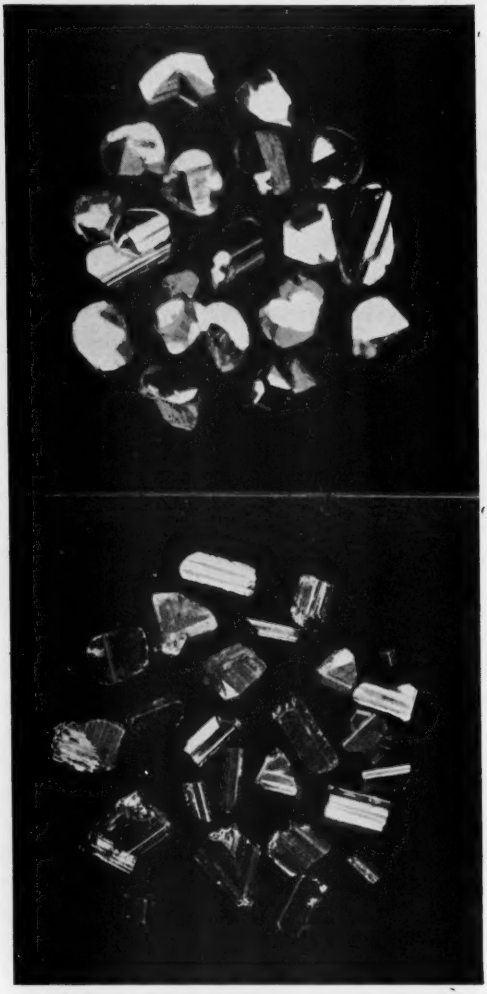

FIG. 1. *A*. Crystals of synthetic calaverite. ×25. *B*. Calaverite from Cripple Creek. ×3.

Experiments were undertaken to see if gold telluride can be made in aqueous systems which include alkali polytelluride. A solution was prepared consisting of equal parts by weight of $Na_2S.9H_2O$ and water. This was saturated at room temperature and atmospheric pressure with hydrogen sulphide. Approximately 30 cc. of the resultant solution was transferred to a pyrex reaction tube and about 1 gram of a mixture of granular gold and tellurium in equal atomic proportions added. The air above the solution was displaced with hydrogen sulphide and the tube sealed off. It was placed in a water-bath ($90° \pm 5°$ C.) and the contents were vigorously shaken every few days. After several hours, the silvery metallic particles of tellurium were being replaced by a dark brown, fine-grained substance. At the end of 10 days, all of the original tellurium appeared to have been completely replaced, but there still remained visible particles of gold. In addition, in a strong light, small metallic reflections could be seen which were of a pale yellow color. After 20 days in the water-bath, the tube was opened. The clear solution was very pale yellow and contained both gold and tellurium. The mixture of fine-grained solids consisted of unaltered gold, and a dark brown substance. This was washed thoroughly with water and then agitated with mercury, which removed most of the gold. The dark brown residue was dried and examined by the *x*-ray powder diffraction method. The pattern of gold was strong, and the two strongest lines of calaverite were present, but only as exceedingly faint, broad lines. It was concluded that crystalline calaverite was either not formed, or formed only in very small amount, by this method.

A similar experiment was carried out at a higher temperature. A solution of equal parts by weight of $Na_2S.9H_2O$ and water was saturated with hydrogen sulphide, and 36 cc. placed inside the graphite-lined steel bomb. The internal volume of the bomb was 72 cc. Approximately 0.75 gram of gold shavings and 1.0 gram of crushed metallic tellurium were added to the solution. The bomb was sealed, heated to 245° C. in 1 hour, and kept at about this temperature for 15 hours. No smell of hydrogen

sulphide was noticed when the bomb was opened. The solution was pale yellow, and growing out from the sides of the graphite lining were needle-like crystals. The gold shavings still preserved their original shape. The solution contained abundant tellurium but no gold. The long slender crystals proved to be metallic tellurium. The gold shavings were thinly coated with a crystalline aggregate of very pale yellow, silvery color, very similar in appearance to calaverite. Growing on the shavings were many crystals of tellurium and also small, imperfect, soft, dark purple crystals of unknown composition. Apparently the tellurium was reversibly soluble in the solution used, dissolving as polytelluride at elevated temperatures and precipitating on cooling. The polytelluride complex attacked the gold, forming gold telluride, but the conditions were not such that this compound was appreciably soluble in the solution, and good crystals were not formed.

A similar experiment, but employing more concentrated solutions and higher temperatures, was performed. Approximately 0.5 gram of gold, 0.75 gram of tellurium, 0.2 gram of sulphur and 4.0 grams of sodium sulphide were first fused together. This gave a dark purplish-brown crystalline mixture which was broken up and placed in the graphite-lined steel bomb (72 cc. inside volume), and 6 grams of water added. The bomb was sealed, heated to 400° C. in 2 hours, kept at this temperature 1 hour, and then slowly cooled to room temperature in 18 hours. There was no smell of hydrogen sulphide when the bomb was opened. In the bottom of the bomb was a dark solution with an abundance of large black crystals of a soluble tellurium compound and a few small, pale yellow, metallic crystals. The solution was deep violet but this color disappeared in a few hours when exposed to the air, and metallic tellurium was precipitated. The pale yellow material consisted of two types: one was flaky and apparently non-crystalline, and the other was in the form of small, perfect crystals. The flaky material was washed from the heavy crystals, which were then dried and examined. They were 0.5 to 1 mm. in size, had a well-developed crystal form (apparently monoclinic) and doubly-terminated, and complex twin crystals

were observed (Fig. 2). The x-ray powder diffraction pattern of the crystals was found to be the same as that given by Harcourt (1942) for calaverite ($AuTe_2$), and is shown in Fig. 1 with the pattern of calaverite from the type locality, Cripple Creek.

It was concluded from these attempts to synthesize gold telluride that in alkali sulphide solutions, gold telluride is less soluble than gold sulphide, which in turn is less soluble than tellurium sulphide, and also that gold telluride appears in alkali sulphide systems only when the free sulphur concentration is low.

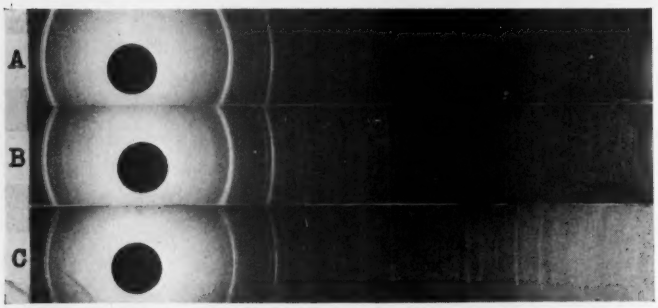

FIG. 2. *A*. Calaverite prepared in a Na_2 (S, Te)$_x$ fusion. *B*. Calaverite prepared in a Na_2 (S, Te)$_x$ solution. *C*. Calaverite from Cripple Creek. The x-ray patterns were obtained with Cu radiation and Ni filter using a camera with radius $360/4\pi$ mm.; 1 mm. on film $= 1° \theta$.

The successful crystallization of metallic gold, electrum, and calaverite in aqueous solutions of alkali sulphide is presented as support for the hypothesis being tested: that natural ore-bearing solutions which deposit these minerals may be alkali sulphide solutions.

DISCUSSION

The solubility of metallic sulphides in aqueous solutions of sodium sulphide has been shown to be dependent on the sodium sulphide concentration. Thus anhydrous fusions of sodium sulphide and polysulphide are considerably better solvents for metallic sulphides than aqueous solutions of sodium sulphide and

polysulphide. It was also shown that the simple metallic sulphides are precipitated if the sulphide concentration of solutions of sodium thiometallic salts is lowered sufficiently, and if it is very low, metals rather than their sulphides, can be made to separate. Since it has been postulated that natural ore-bearing solutions contain alkali sulphide, the geological conditions which will bring about a lowering of the sulphide concentration should be considered.

The factors in nature which lead to a lowering of the sulphide concentration of ore-bearing solutions may be highly complex, but a few of the simpler ones may be discussed. Loss of hydrogen sulphide by separation of the ore-bearing solution into two phases, one liquid and one gaseous, is considered to be of relatively minor importance, especially in the deeper types of ore deposits. It may be of importance, however, in the low-pressure regions of near-surface vulcanism. In such regions, escape of hydrogen sulphide has been repeatedly noticed, the sulphurous smell of fumaroles and hot springs in such regions generally being due to hydrogen sulphide. Of probably greater geological significance is the loss of sulphide ion due to the action of the ore-bearing solutions on the minerals of the rocks traversed. There are three general reactions which are of importance in this connection. One, not so common as the others, is due to oxidation of sulphide ion to sulphate ion by oxidizing minerals in the wallrock. The effect of this has been noticed at Keweenaw Point by Butler, Burbank, *et al.* (1929). Hematite in the lava flows through which the solutions circulated was converted into ferrous minerals and native copper was simultaneously precipitated. The apparent rarity of this type of reaction is probably due to the infrequent occurrence of minerals in a high state of oxidation making up a large percentage of crustal rocks. The second process, and doubtless the most important, is the conversion of iron minerals in the wallrock to sulphides, predominantly pyrite. In most ore deposits pyritization of the wallrock has occurred, sometimes in very large amounts, though the pyrite is usually disseminated in rather small crystals through the body

of the altered rock. The third process, not as important, is the conversion of aluminum minerals in the wallrock to alunite $(Na, K)_2Al_6(OH)_{12}(SO_4)_4$, or minerals of that general type. This reaction does not appear to be very common in the ore deposits formed at relatively high pressures, but is very extensive in some regions, notably in the Goldfield district, Nevada (Ransome 1907). Apparently in cases of alunitization, the sulphate concentration of the solutions responsible for the alteration is high, and this has been shown to take place in complex alkali sulphide solutions when the hydrogen sulphide is allowed to escape. This, of course, would be much more common under low-pressure than under high-pressure conditions. In reality, the first and third processes are two expressions of the same reaction, with concurrent loss of hydrogen sulphide and increase in sulphate ion. Another factor in reducing the sulphide concentration of ore-bearing solutions would be dilution by meteoric water. A condition might exist in which hydrothermal solutions of magmatic origin would enter the zone of abundant groundwater. The mixing of the two solutions would result in cooling, partial oxidation of sulphide ion to sulphate ion, and displacement of hydrolysis equilibria in such a way that the sulphide ion concentration would be greatly reduced. All of these changes would tend to break down the soluble alkali thiometallic compounds and precipitate metallic sulphides, or free metals. This is more than a hypothetical possibility, since it has been observed in the mercury deposits in the Terlingua District, Texas, by C. P. Ross (1941), but it is not likely of great importance in most ore deposits.

Although gold is very soluble in alkali sulphide solutions, forming complex thioaurites, it separates from such solutions as the metal, and not as a sulphide, when the sulphide ion concentration is reduced to the point where the complex is broken down, even though the concentration of free sulphur (polysulphide ion) is high compared to the concentration of the sulphide ion. This is apparently due to the great instability of gold sulphide.

When tellurium is present in homogeneous systems including gold and sodium sulphide, the concentration of free sulphur (as

polysulphide ion) influences the course of events as the sulphide ion concentration is reduced. If the amount of free sulphur is small, then some thiotellurite ion is decomposed, forming polytelluride ion, and this appears to react with thioaurite ion, precipitating gold polytelluride ($AuTe_2$). If the free sulphur concentration is large, all the thioaurite ion is decomposed before the thiotellurite ion, and thus metallic gold is precipitated before metallic tellurium, and gold telluride is not formed. It would therefore appear that the conditions of deposition of calaverite are somewhat restricted, and in nature these conditions are apparently not often satisfied, since metallic gold occurs much more frequently than the gold telluride. If both occur in a gold ore, metallic gold is generally found to have been precipitated after gold telluride.

There may be other methods of gold precipitation operative in nature. For instance, adsorption by colloids may be the reason why ubiquitous minerals such as pyrite and quartz often are auriferous. Some experimental support for this was obtained, and it is hoped that further data will permit publication of this supplementary information.

CONCLUSION: A THEORY OF GOLD ORE DEPOSITION.

The types of gold ores which have been considered and to which the following theory of formation can be applied, are those which are generally referred to as "primary." They are generally in, or related to, faults in the rocks in which they occur, and contain many minerals which are not stable under atmospheric conditions, the most important being the sulphides of the heavy metals.

Following the generally accepted theory, it is believed that metalliferous ores including gold ores are derived from igneous intrusives. The process of separation of ore-bearing fluids from the magma is undoubtedly highly complex, but the general sequence of events is believed to be somewhat as follows. A large igneous intrusive is forcibly emplaced into rocks cooler than itself. The magma at the time of emplacement is at least partly in the liquid condition, the liquid part containing the elements necessary

for the formation of the common rock-forming silicates, and in addition, the components of the magma which are present in relatively small amounts and which do not readily separate along with crystalline silicates. Of these, water is the most important, but compounds containing sulphur, chlorine, and the heavy metals are also present along with minor amounts of practically all of the common and rare elements. As the magma cools, silicates separate and the residual liquid becomes richer in the rare components we have mentioned. At a late stage in the crystallization of the magma, the residual liquid may be considered to be an aqueous solution containing some of the elements of the latest silicate minerals that have crystallized. The latest silicate minerals being generally alkali alumino-silicates, the aqueous solution in contact with them is believed to be strongly alkaline in the ordinary use of the term. This aqueous residual solution is expelled from the magma by forces which may include the continuation of those which intruded the parent magma, and also the force of increasing vapor pressure of the residual solution as it becomes richer in the volatile compounds, especially water. Channels of escape into the surrounding rocks may be provided by local crustal disturbance associated with the now nearly solid intrusive mass. The solutions derived from the magma in this way are believed to be the normal ore-depositing agents. This process of formation of ore-bearing solutions rests on the presumption that the pressure prevailing at all times is so high that only condensed systems are possible, so that no distinction need be made between solutions which, if the pressure were released, would expand indefinitely with no separation of a second fluid phase and those which would form a second fluid phase.

The composition of the ore-bearing solutions when first separated from the magma is believed to be alkaline, and the most characteristic compounds which they deposit on cooling are alkali silicates, quartz, and metallic sulphides. The oxycompounds are believed to be carried in the form of double oxides with alkali metal, such as sodium silicate, and breakdown of the complex double oxides precipitates simple oxides such as silica. Since the

solutions also transport and deposit metallic sulphides, a consideration of the reactions necessary for this condition in alkaline solutions leads to the conclusion that alkaline sulphide must be present in abundant excess. As is well known, alkali sulphide readily forms double sulphides with metallic sulphides. It is believed that the metals are carried in the double sulphide form and are precipitated as the simple sulphides when the double complex is broken down. Thus the development of a theory of deposition of any one of the metals will depend largely upon the chemical properties of the double sulphides of that metal and alkali metals. Since sodium appears to be the most common alkali metal present in remnants of the ore-depositing fluids, such as liquid inclusions in minerals, and hot springs, the chemical data upon which the following theory of gold deposition is based will be largely the properties of the double sulphides of gold and sodium.

Processes in nature which affect the sulphide concentration of ore-bearing solutions will control the deposition of the metals. Action of the solutions on the minerals of the rocks through which they pass, escape of hydrogen sulphide, and dilution by meteoric water are probably the most important reactions which reduce the sulphide concentration. The wallrock may lower the sulphide and polysulphide concentration by changing iron-bearing minerals to pyrite. Less frequently the sulphate concentration may be lowered by the alteration of aluminum-bearing minerals to alunite. Such lowering of the sulphate concentration displaces the homogeneous equilibrium in complex alkali sulphide solutions in such a way that there is a concurrent lowering of the sulphide and polysulphide concentration. Loss of hydrogen sulphide by boiling at relatively low pressures is probably not common in nature. Escape of hydrogen sulphide, however, would displace the equilibrium mentioned above in such a way that the sulphide and polysulphide concentration would decrease and the sulphate concentration would increase. Dilution by meteoric water would lower the sulphide concentration and in addition would in some cases oxidize some sulphide ion to sulphate ion. Thus the deposition of metallic sulphides carried in ore-bearing solutions as

complex double sulphides would result from pyritization and alunitization of the wallrock, loss of hydrogen sulphide, and dilution by ground water.

Gold is much more soluble than most of the common metals in alkali sulphide solutions. It is included in the group of metals whose sulphides are very soluble in dilute aqueous solutions of alkali sulphide at ordinary temperature. This group also contains mercury, bismuth, antimony, arsenic and tellurium. In the group of metals whose sulphides are soluble in aqueous solutions of alkali sulphide only at elevated temperature, the most soluble metal appears to be silver. Thus the natural association of minerals containing gold which are deposited late in the ore sequence with minerals containing silver, bismuth, and tellurium is explained. When the soluble double sulphides of gold and alkali are broken down by a lowering of the sulphide concentration, gold deposits as the metal, since its sulphides are very unstable above 40° C. In solutions containing both silver and gold, if the sulphide concentration is reduced to the point where metallic gold separates, it does so along with considerable silver in solid solution, forming argentiferous gold or electrum.

If tellurium is present along with gold in natural alkali sulphide solutions, gold tellurides may or may not precipitate as the sulphide concentration is reduced, depending on the state of the tellurium in the solutions. If the free sulphur concentration in the polysulphide form is high, then the tellurium is present as alkali thiotellurites, and when in this form metallic gold precipitates first and much later the thiotellurite complex is broken down and metallic tellurium is precipitated. If the free sulphur concentration is low, then the tellurium is present in part as polytelluride ion, and gold tellurides are first precipitated, followed later by the excess of metallic gold. These reactions have been duplicated by experiment, the order of solubility in alkali sulphide solutions being found to be, starting with the most insoluble—gold telluride, gold, tellurium. This explains the natural paragenesis of gold tellurides, gold, and tellurium, which apparently deposit in the same order.

ACKNOWLEDGMENTS.

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March 15, 1943.

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THE MANGANESE DEPOSITS OF THE TURTLE MOUNTAINS, NORTH DAKOTA.[1]

THOMAS A. HENDRICKS[2] AND WILSON M. LAIRD.[3]

ABSTRACT.

The principal manganese spring deposits in the Turtle Mountains of North Dakota were investigated and mapped in detail. One of these, Mineral Spring, located in the N½ NE¼ Section 22, T. 162 N., R. 73 W., was found to contain approximately 16,000 tons of manganese ore in the form of the mineral ranciéite in calcareous tufa with an average manganese content of about 10 per cent. The source of the manganese appears to be in manganiferous limonitic concretions in the Fort Union formation which underlies the glacial drift in the Turtle Mountains.

INTRODUCTION.

General Statement. The manganese deposits of the Turtle Mountains have been known for many years but no detailed report of these deposits has been published. Manganese at present is classified as a strategic metal and search for domestic supplies has therefore been accelerated. Parts of the deposits of the Turtle Mountains, though small, are of considerable scientific interest.

Location. The Turtle Mountains are located in the northwestern part of Rolette County and the northeastern part of Bottineau County, North Dakota, in townships 161–164 north and ranges 70–77 west; they extend into the province of Manitoba, Canada.

Three of the spring deposits contain abundant evidences of manganese. These are: Mineral Spring (N½ NE¼ Section 22, T. 162 N., R. 73 W.), Holy Spring (SE¼ Section 25, T. 162 N., R. 72 W.), and an unnamed spring north of Dunseith (NE¼ NW¼ Section 30, T. 162 N., R. 72 W.).

[1] Published by permission of the Director, Geological Survey, United States Department of the Interior.

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Method of Study. The deposits were surveyed with a plane table and alidade. At selected localities, bore holes, hand-drilled with a four-inch post-hole auger, were put down to determine the thickness of the deposits. Samples were taken at several places to obtain an average manganese content of the deposit.

Physiography. The area occupied by the Turtle Mountains is an oval-shaped upland 25 miles in width by 40 miles in length extending into the province of Manitoba, Canada. The "mountains" attain altitudes of as much as 2,300 feet above sea level and stand 400–700 feet above the surrounding plain.

Geologically, the Turtle Mountains consist of a core of bedrock of the Fort Union formation (Paleocene) mantled by a thick covering of glacial debris. The glacial till is in the form of recessional moraines which, on the mountains proper, exhibit typical recessional moraine topography, knobs and kettles, some of which contain lakes whereas others are only undrained depressions. The surface of the mountains is definitely youthful, as well-integrated drainage has yet to be established.

The plain surrounding the mountains, particularly on the south, appears to be a mixture of ground moraine and glacial outwash. In many places, the ground moraine seems to have been partly covered by the outwash. The plain near the mountains is studded with lakes and undrained depressions, due perhaps either to buried pre-glacial drainage or to the melting of buried ice blocks, or both.

STRATIGRAPHY.

Tertiary.

Paleocene.

Fort Union formation. The bed rock in the Turtle Mountains is so effectively covered with glacial drift that very little is known about it. Because of the occurrence of lignite in the area [4] it has been inferred that the bed rock immediately below the drift is a part of the Fort Union formation. The lignite, however, has been seen in only one exposure and so little else is known of the bed rock in the Turtle Mountains that it will not be extensively discussed in this report.

The single outcrop is located in the SW¼ NW¼ Section 7, T. 162 N., R. 76 W., along State Route 14, 5 miles north of Carbury, Bottineau County, North Dakota. Lignite has been reported [5] as occurring two miles north of Dunseith, Rolette County, in an old mine shaft. The lignite had a dip of 30° to the north according to Babcock.[6] Mr. Gottbreht, who was financially interested in the mine, reports that the lignite was apparently a "slide." The possibility of faulting should also be tentatively considered, particularly in view of the fact that the manganese-bearing springs are situated along a line approximately parallel to a projection of this "slide."

The Fort Union formation consists predominantly of light, ash-gray, yellow to brown-colored sands and clays with darker lignitic shales and lignites. The sands are fine-grained and usually not well indurated except in certain areas where quartzitic concretions due to case-hardening have been formed. The clays are thin-bedded and at places contain considerable amounts of bentonite. Owing to the fact that the Fort Union formation is predominantly

[4] Babcock, E. J.: North Dakota Geol. Surv. 1st Bienn. Rept., p. 71, 1901. Wilder, F. A.: The lignite coal fields of North Dakota. North Dakota Geol. Surv. 2nd Bienn. Rept., p. 162, 1902. Leonard, A. G.: The geological formations of North Dakota. North Dakota Geol. Surv. 3rd Bienn. Rept., p. 154, 1904.

[5] Babcock, E. J.: op. cit. Wilder, F. A.: op. cit. Leonard, A. G.: op. cit. Personal communication from Mr. William Gottbreht of Dunseith, N. Dakota.

[6] Babcock, E. J.: op. cit., p. 71.

continental, the beds are characteristically lenticular. The color does not change much on weathering, the brown and gray being largely retained.

The character and composition of the bed rock are important, as it is one of the possible sources, if not the most probable source, of the manganese in the Turtle Mountain deposits. In the outcrop north of Carbury, there is a considerable thickness of gray, fine-grained sand, brown, fine-grained sand and gray and brown shale with some thin lignitic shale stringers. Interbedded with the shales and sands are a few limonitic concretionary layers which contain a trace of manganese.[7]

Pleistocene.

Late Wisconsin. The glacial deposits of the Turtle Mountains are practically unstudied and very little detailed information is available. The deposits are primarily glacial recessional moraine of late Wisconsin age with glacial outwash forming a more or less regular apron around the mountains, particularly to the south. Interspersed in this apron of outwash are what appear to be irregular patches of ground moraine. The glacial deposits of the Turtle Mountains have been reported by Leonard [8] as being from 100 to 200 feet thick. At certain places, such as at the well located in the SE¼ Section 36, T. 164 N., R. 73 W., the drift is much thicker. At this locality gravel is reported to be 455 feet below the surface with the possibility that 20 feet more may also be glacial till. This excessive thickness may be due to the filling of a pre-glacial valley.

THE MANGANESE DEPOSITS.

All three of the manganese deposits investigated in the Turtle Mountains have been formed around cold springs. The manganese is in the form of ranciéite,[9] a finely flaky, soft, brownish-

[7] The sample was tested by Miss Adelynn Magnusson, analyst, of the School of Mines at the University of North Dakota at Grand Forks.

[8] Leonard, A. G.: The surface features of North Dakota and their origin. Univ. North Dakota Bull. 14, no. 1: 20, 1930.

[9] Fleischer, Michael and Richmond, W. E.: The manganese oxide minerals, a preliminary report. ECON. GEOL., 38: 269–286, 1943.

black, hydrous calcium-manganese oxide, mixed with calcium carbonate in the form of calcareous tufa.

Mineral Spring. The most important manganese deposits investigated are those at Mineral Spring located in the N½ of the NE¼ of Section 22, T. 162 N., R. 73 W. The manganese in this locality is found in two different deposits about 150 feet apart (Fig. 1). The deposit farthest west is a circular mound 50 feet in diameter and about 6 feet above the surface of the swamp surrounding it. The center of the mound is so swampy that the depth was not determined. The outside of the mound consists entirely of porous, dry, earthy manganese oxide and calcareous tufa. Owing to the hardness of tufa, the depth of this deposit could not be determined with the post-hole auger.

The main manganese deposit at Mineral Spring lies about 150 feet east of the above-mentioned mound. This deposit is approximately rectangular in shape, with an effective length of 260 feet and a width of 150 feet. From data gathered from holes put down by hand auger, it appears that the deposit has a maximum thickness of 15 feet, and is lens-shaped in cross-section.

This main deposit is in the form of a layer of porous wad and calcareous tufa blanketing the hillside. The upper part where the water from the present spring opening emerges is basin-shaped. The rim of this basin is about 2 feet above the present water level of the spring basin, suggesting that either there is less water now, or that the rim of the basin has been breached.

Using the figures above-mentioned (260×150 feet) and assuming an average thickness of 10 feet, this deposit on the east side of the road (Fig. 1) contains 390,000 cubic feet. According to a Department of the Interior Press Memorandum,[10] about 25 cubic feet of this material constitutes a ton. This would mean that there are 15,600 tons of manganese and calcareous tufa in the main part of the deposit. Using a diameter of 50 feet and a height of 6 feet for the mound on the west side of the road, it was found that this mound should contain 472 tons. The total tonnage of the two deposits, then, is approximately 16,000 tons.

[10] U. S. Dept. Interior Press Mem. 158359.

The Mineral Spring deposit is interesting because of the rather clear indications that the spring has had more than one opening. It would appear that the mound (Fig. 1) on the west was the first

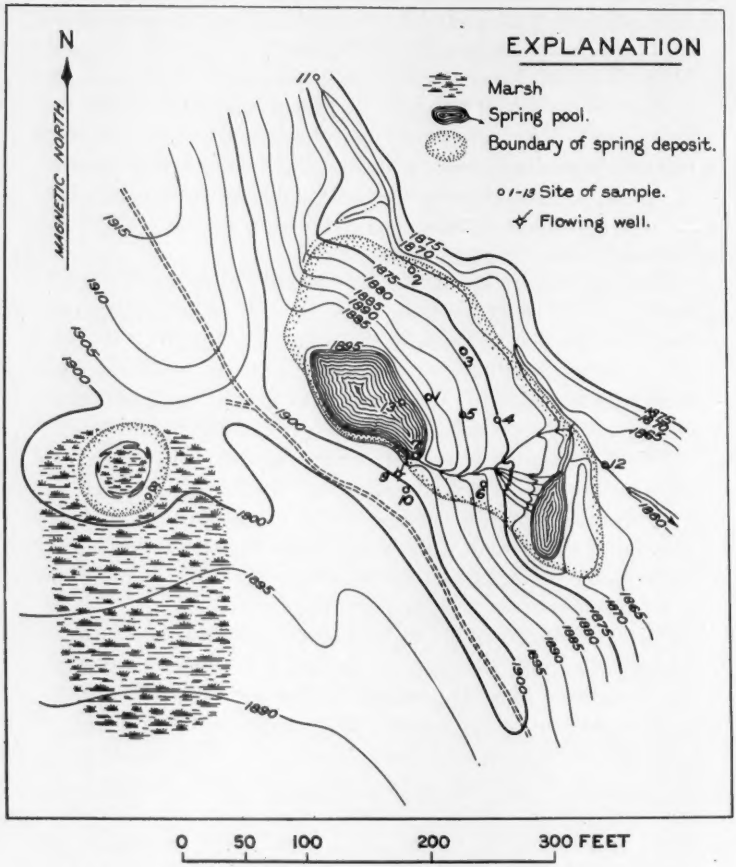


FIG. 1. MAP OF MINERAL SPRING, NE. ¼ Sec. 22, T. 162 N., R. 73 W., Dunseith Quadrangle, North Dakota, T. A. Hendricks and W. R. Wagner.

opening of the spring and that the spring flowed from that opening until the deposition of the manganese and calcareous tufa had built the mound so high that the hydrostatic pressure was no longer sufficient to force the water out that opening. It then broke out at a lower level, forming the main deposit 150 feet east of the mound. The swampy character of the center of the mound and the area surrounding it indicates that the water is still very near the surface on the west side of the road, although the main flow of the spring is on the east side of the road.

There is some evidence of another spring basin 25 feet below the present spring opening. This is shown on Figure 1 southeast of the main spring deposit. A low ridge containing slight amounts of manganiferous tufa is present on the southeast side of a small pool. This basin may be a minor subsidiary opening to the main spring or it may be a former opening of the spring which is not now functioning at full capacity. The more likely explanation seems to be that this is a subsidiary opening.

From the fact that the manganese deposits are resting on glacial till, as was determined by auger holes, it is evident that these deposits have been formed since late Wisconsin time; in fact, as the main deposit is resting on the side of a valley cut in the glacial till, it would appear that there had been some erosion prior to the formation of the main spring deposit.

Spring North of Dunseith. About 1 mile north of Dunseith in the NE¼ of the NW¼ of Section 30, T. 162 N., R. 72 W., there is a spring with a fairly well-developed mound showing traces of manganese. The mound here is roughly elliptical in shape and is about 225 feet in length by 125 feet in width. The center of the mound where the spring emerges is about 10 feet above the surrounding swamp surface. The whole mound is so saturated with water that it was impossible to hand-auger down more than 5 feet. No reliable estimate of the thickness of this deposit, therefore, can be given; the only basis for an estimate is the above-mentioned fact that the mound stands about 10 feet above the surrounding swamp surface.

From surface indications this deposit consists mainly of cal-

careous tufa with only slight amounts of manganese. It would be advisable, however, to make more exhaustive borings before a totally negative report on this deposit is given.

Holy Spring. This manganese-bearing spring is located in the SW¼ of the SW¼ of Section 25, T. 162 N., R. 72 W., 5½ miles east of Dunseith, North Dakota. This spring has a larger flow of water than the other springs investigated, but no mound of manganese or calcareous tufa was found immediately around the spring opening. About 50 or 60 feet below the spring opening and along the stream issuing from the spring there are indications of manganese but in no large amounts.

South of the spring in the NW¼ of the NW¼ of Section 36, T. 162 N., R. 72 W., the stream valley opens into a flat about 500 feet wide. In this flat in two places in the stream, deposits of calcareous tufa were found, but little if any manganese. That the stream is now depositing calcareous material is evidenced by the deposition of that material around sticks and on glacial boulders in the stream bed. As it does not appear that there is manganese in commercial quantities in this deposit, this spring was not mapped.

MODE OF ORIGIN OF THE DEPOSITS.

There appear to be two possible sources of the manganese of the Turtle Mountains; namely, the glacial drift and the bed rock. Samples of the glacial drift were tested for manganese and a trace was found to be present (sample No. 10, Table 1).

As has been noted previously in this report, the bed rock immediately underlying the drift is considered to be Fort Union (Paleocene) in age. If the stratigraphic sequence is normal, the Fort Union should be underlain by the Hell Creek formation of Cretaceous age. Both of these formations in other parts of the State contain ironstone concretions which contain small amounts of manganese. In the files of the North Dakota Geological Survey there are records of analyses made on some "ironstone" concretions from Burleigh County which were collected from either the Fort Union or the Hell Creek. These concretions average 4.8

TABLE 1.

MANGANESE SAMPLES COLLECTED BY T. A. HENDRICKS FROM SECTION 22, T. 162 N., R. 73 W., ROLLETTE COUNTY, NORTH DAKOTA (analyses by Victor North of the Chemical Laboratory, Geological Survey, and checked by analyses by Rolla Experiment Station. Bureau of Mines, United States Department of the Interior).

	1	2	3	4	5	6	8	10 Glacial Till	15
Mn	23.76	3.18	5.32	5.07	18.31	13.76	7.51	0.10	2.91
SiO_2	1.48	0.31	0.72	0.41	1.62	0.71	1.20		0.52
Fe_2O_3	0.23	0.09	0.11	0.03	0.13	0.04	0.08	2.60	0.65
Al_2O_3	0.36	0.21	0.33	0.11	0.42	0.06	0.39		0.67
CaO	26.71	50.38	47.65	48.39	26.20	35.76	42.38	17.8	49.80
P_2O_5	0.04	0.03	0.07	0.06	0.05	0.01	0.05	0.12	0.02

per cent manganese. The concretions collected in the outcrop of the Fort Union north of Carbury contained only a trace of manganese. It would appear, therefore, that the immediately underlying bed rock was the most probable source of the manganese.

Similar manganese spring deposits are reported by Spector [11] from the Riding Mountains in the province of Manitoba, Canada. Here, however, the source was clear, as the Odanah beds (upper Pierre age), which crop out in the Riding Mountains, contain manganiferous concretions. The analysis of one concretion from the Odanah shale contained 4.44 per cent of manganese dioxide.[12] Hewett [13] points out there is no good evidence that excessive accumulations of manganese in sedimentary deposits depend on excessive percentages in the rocks surrounding the basin in which the waters entering the basin rise; therefore, even the trace of manganese reported in the concretion from the Fort Union north of Carbury, North Dakota, might be sufficient for the Turtle Mountain deposits.

Hewett [14] also states that manganiferous carbonates are much more widespread in unweathered sediments than the oxides. If

[11] Spector, I. H.: Manganese deposits in the Riding Mountain area, Manitoba. The Pre-Cambrian, July, 1941, pp. 49–51.

[12] Idem., p. 51.

[13] In Twenhofel, W. T.: Treatise on Sedimentation, 2nd edit. Williams and Wilkins Co., Baltimore, 1932, p. 578.

[14] Idem., p. 563.

the manganese is in this form in the bed rock, then carbonated waters circulating through the bed rock could leach the manganese out of the nodules and carry it in the form of manganese bicarbonate. According to Savage [15] this manganese bicarbonate would remain in solution until the water issued from a spring where the solution would become slightly alkaline through the action of aeration, the presence of calcium carbonate, or thread bacteria. Zappfe [16] has shown that once the manganese oxide began to form it would act as a catalyst in precipitating additional manganese oxide from solution.

Possibly reactions similar to those occuring in the Riding Mountains of Canada took place in the Dunseith Mineral Spring deposits; however, in view of the fact that the mineral of the Mineral Spring deposits appears to be the rather rare species of manganese determined by mineralogists of the United States Geological Survey [17] to be ranciéite, the reactions are not in every respect identical. Ranciéite is a hydrous calcium-manganese oxide. The manganese may originally have been in solution as manganese bicarbonate; the calcium may have entered into the compound when the ground water bearing the manganese bicarbonate solution came in contact with the glacial till, as the till is very calcareous.

Apparently ranciéite does not have the same catalytic effect on manganese in solution as pyrolusite (MnO_2) has. Zappfe [18] has shown that pyrolusite causes immediate and apparently complete precipitation of all manganese in solution when the manganese-bearing solution comes in contact with it. The waters of the stream below Mineral Spring (sample No. 12, Table 2), however, were found to contain 7 parts per million of precipitated manganese. When the sample was taken, the water was clear so the precipitation apparently took place after sampling. This precipitate would indicate that the ranciéite does not have the same catalytic effect that pyrolusite does.

[15] Savage, W. S.: Solution, transportation and precipitation of manganese. ECON. GEOL., 31: 292, 1936.

[16] Zappfe, C.: Deposition of manganese. ECON. GEOL., 26: 824, 1931.

[17] Fleischer, Michael, and Richmond, W. E.: op. cit.

[18] Op. cit., pp. 816, 824.

TABLE 2.

PARTIAL ANALYSIS OF WATER FROM NEAR DUNSEITH BY N. A. TALVITIES.

	Parts per Million			
	7	9	11 Above Spring	12 Below Spring
Manganese (Mn)				
In solution	0.3	2.0	0	0
Precipitated	1.9	0.08	0.04	7.00
Bicarbonate (HCO_3)	530.00	540.00	334.00	486.00
Sulphate (SO_4) Approx.	340.00	360.00	400.00	440.00
Chloride (Cl)	6.00	7.00	4.00	7.00
Total hardness as $CaCO_3$	678.00	720.00	624.00	744.00

It was thought in the field that part of the manganese in the waters below Mineral Spring might have come from other sources. To test this possibility, a sample of water from the stream above the spring was taken (sample No 11, Table 2) and found to contain only 0.04 part per million of precipitated manganese. It would thus appear that the greater part of the manganese in the water below the spring undoubtedly came from Mineral Spring.

The exact cause of the precipitation of ranciéite is not known, but it may be suggested that the escape of hydrogen sulphide (H_2S) and the deposition of calcium carbonate ($CaCO_3$) in the form of calcareous tufa caused a change in the pH of the water which, together with aeration, resulted in precipitation of some of the manganese and calcium as ranciéite.

ANALYSIS OF THE ORE.

The analyses of the manganese ore at Mineral Spring show that it is definitely of low grade. The manganese content of the samples can be seen by reference to Table 1. The manganese content of these samples (neglecting sample No. 10, which is a sample of glacial till) ranges from 3.18 to 23.76 per cent and averages 9.97 per cent. It will be noted that in the samples showing a high manganese content the percentage of calcium carbonate is relatively low; conversely where the percentage of calcium carbonate is high the manganese content is low. The ores can thus

be divided roughly into two types; a "soft" ore high in manganese and a "hard" ore lower in manganese and higher in calcium carbonate in the form of tufa.

A sample of the crude ore was supplied to Mr. S. M. Shelton, Supervising Engineer of the Rolla Experiment Station of the Bureau of Mines, United States Department of the Interior. Mr. Shelton kindly prepared, by flotation with sodium oleate and dextrin, a concentrate free of calcium carbonate or other impurities in significant amounts. A sample of this pure material was photographed with x-rays and found to give the diffraction pattern of ranciéite. A complete chemical analysis of the sample was then made by Michael Fleischer of the Chemical Laboratory of the Geological Survey. It is quoted below.

Analysis of a flotation concentrate of ranciéite from Mineral Spring.

MnO_2	66.26	TiO_2	None	
MnO	1.37	CO_2	2.60	
Al_2O_3	0.19	P_2O_5	None	
Fe_2O_3	0.30	NiO	0.12	
MgO	0.97	CoO	0.06	
CaO	9.43	BaO	0.07	
Na_2O	0.74	Li_2O	0.005	
K_2O	0.74	CuO	None	
H_2O-	3.95	PbO	0.05	
H_2O+	10.45	Bi_2O_3	0.17	
		Insol	3.65	(largely organic matter)
		Total	101.42	

The total of 101.42 is in excess of 100 per cent because the insoluble organic matter gives off water, making the figure for water too high. Of the 9.43 per cent of CaO, 3.31 per cent is present as calcium carbonate that was not eliminated from the concentrate in the flotation process.

The analysis and the x-ray lattice spacing of ranciéite indicates that its composition is (Ca, Mn^{II}) $Mn_4{}^{IV}O_9 . 3H_2O$.

April 14, 1943.

DISCUSSION AND COMMUNICATIONS

A METHOD FOR COLLECTING ORIENTED MINERAL SPECIMENS.

In the process of collecting mineral specimens in the Wisconsin zinc district, the writer was confronted with the problem of securing pieces of ore, gangue, and rock which could be correctly oriented in the laboratory, where sectioning and polishing were to be carried out as a prelude to the study of preferred growth characteristics. As the study was designed to throw light on the direction of flow of mineralizing solutions, it was desirable to record the horizontal distribution of specimens collected, and also the approximate vertical relations of closely grouped specimens as well as the more or less exact orientation of each specimen in space, and particularly so with reference to the local orebody, such as "pitch" (inclined fracture), vertical, or "flat" (bedded vein) from which the specimen was removed.

The writer makes no claims to having originated the collecting technique briefly described below, and experienced workers in petrofabrics may consider it too elemental and obvious to require discussion. It is here outlined, however, in the hope that it may serve geologists studying problems dealing with the direction of solution movements in ore deposition or otherwise concerned with the accurate location or orientation of hand specimens for megascopic or microscopic study.

To correctly orient a specimen in space (or with relation to the earth's axis) it is necessary to establish the strike and dip characteristics of a reasonably flat face. This may seem obvious enough but the writer has heard suggestions that it could be done by establishing the direction and inclination of a bearing line which could be any reasonably straight corner or line marked on the specimen. A bearing line alone marked more or less parallel

to the long dimension of a tilted, tabular specimen would roughly indicate which end was topmost and which bottommost, but obviously the specimen might be rotated 360° about the bearing line as an axis without changing the attitude of the line. It is, therefore, necessary to find a specimen with a reasonably flat face to which the edge of the Brunton may be applied, or to modify the specimen with a few strokes of hammer or chisel. When such a face has been found or constructed, strike and dip lines may be scratched thereon. The writer has found that a castoff dentist's pick makes a very useful tool for scratching, the horizontal edge of the Brunton serving as a straight edge.

Often a nearly vertical face will be chosen, especially when working in mines. When this occurs the dip is obviously vertical and it is necessary to show the bearing of one end of the strike line. If this information were not provided the specimen might be switched end for end in the laboratory without clue as to the correct orientation. It is obvious that if the amount and approximate direction of dip were noted or scratched on an inclined face, together with the strike, the specimen could have only one orientation.

In the case of a horizontal face, the direction of bearing of one end of the strike line is also necessary. In practice the writer always indicates the bearing of one end of the strike line so that information will not be overlooked when orienting vertical and horizontal faces.

A word of caution may be in order against attempting to use a compass in orienting mineral specimens containing or associated with magnetite or pyrrhotite, and too close to mine rails, power lines, drill steel, hammers, and similar highly magnetic objects.

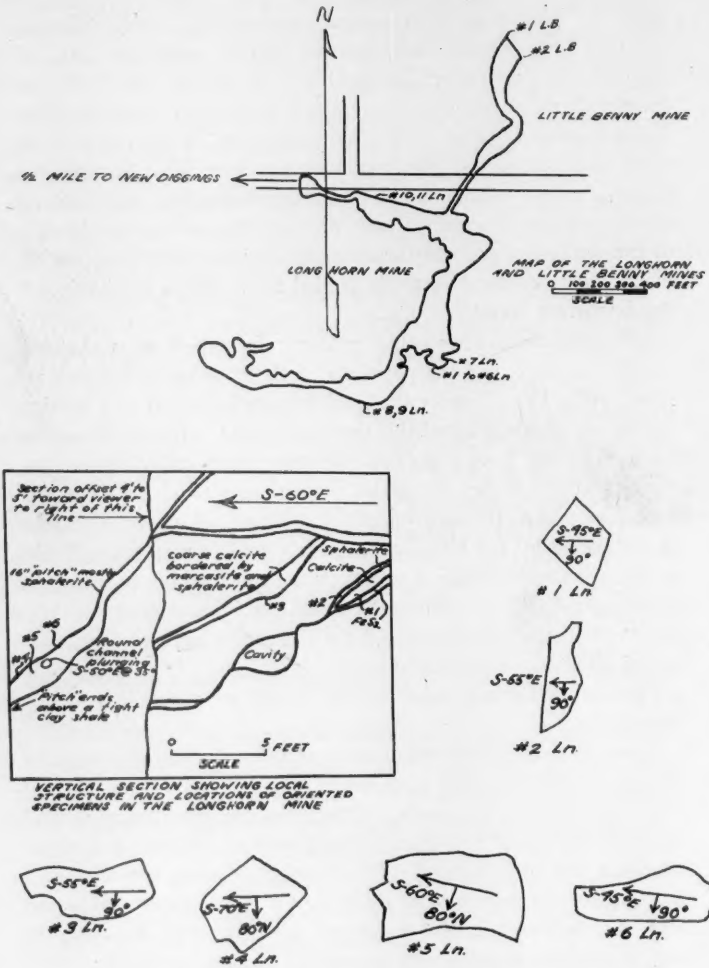
The writer has noted reference to affixing adhesive tape to specimens for the purpose of inscribing orientation data. He has found this technique to be useless in wet mines as the tape refuses to adhere to the damp specimens.

After an operating mine has been visited and specimens secured, the mine may be abandoned and allowed to flood; this prevents entry at a future date. It is, therefore, important that the orien-

tation of specimens be recorded permanently. The following technique has proven satisfactory. Strike and dip data are scratched on the face of the specimens as well as may be in frequently cramped and wet quarters and by light of a carbide lamp. In his note book (Fig. 1) the writer then enters the name of the mine and number of the specimen (as number 5 Longhorn), makes a rough outline sketch of the specimen face on which the orientation was determined, and indicates the position and bearing of the strike line and the direction and amount of dip of the dip line. No reference to scale is needed as the shape of the face is the important thing.

The local fissure or other geologic feature is also sketched roughly to scale, and the positions of the collected specimens are noted (Fig. 1). Usually the local feature is shown as a vertical section and the bearing of this section is noted. It will, of course, be necessary to have a map of the mine when collecting is done underground. Often an outline map of part or all of the workings is available through operators. Maps not up to date may be completed by the investigator or a complete map made. The writer usually uses the compass and pace method of mapping underground; this is sufficiently accurate for his purposes. Positions of collected specimens and the associated features are shown on the mine map as indicated by the sketch map (Fig. 1) showing preliminary collecting done in the Longhorn and Little Benny mines.

Labor is saved if specimens selected for collecting are loosened slightly by careful work with hammer and chisel before orientation observations are made. Otherwise the face selected and oriented may fly off into the Stygian gloom of the mine before the specimen can be dislodged. The number of each specimen and the name of the mine may be noted on a scrap of paper and placed with the specimen before wrapping it. Thorough bundling in old newspaper protects the specimens during transport. The writer has found the game pocket of a duck coat makes a good receptacle for specimens and leaves the hands free for negotiating the tricky passages common to many mines.



METHOD OF TAKING NOTES WHEN COLLECTING ORIENTED SPECIMENS

FIG. 1. To illustrate the method of marking and note taking; the figure represents a page of field notes.

After the specimens have been taken to office or laboratory, their wrappings are removed and the specimens are allowed to dry for several days. When dried they should be permanently and legibly marked so that no trouble may be encountered when determining orientation for sectioning and microscopic study. Actually only a strike line scratched on the specimen face would be necessary for a guide in permanent marking as all pertinent data may be taken from the notebook provided that the outline of the

FIG. 2.

oriented face and the approximate positions and numerical values of the bearings of strike and dip have been noted so that the data may be transferred from the notebook to the dry face of the specimen. On dark colored specimens such as sphalerite, galena, oxidized marcasite, etc., white paint applied with a fine sable hair brush provides permanent and legible markings, whereas light colored specimens (such as secondary calcite) are best marked in India ink or black paint. The name of the mine or locality and the number of the specimen may also be indicated; for example, No. 3 Longhorn may be abbreviated to No. 3 Ln. In the speci-

mens shown photographed for purposes of illustration (Fig. 2), it so happened that four of the faces had near vertical dips, while two had dips of 80° in a northeasterly direction.

RAY E. MORGAN.

April 14, 1943.

THE WORD "MICROFACIES." [1]

Mr. John S. Brown,[2] in proposing the new word "microfacies," omitted to define it, but one gathers that it means "microscopic features," or "appearance under the microscope." Appropriate uses would then be exemplified by saying "the rock has the microfacies of a devitrified tuff" or "of an altered quartz monzonite," or "the rocks, though similar in microfacies, differ in megascopic appearance."

But if we are to have "microfacies," why not "megafacies" also? The question arises, however, whether a reader might suppose that the first meant a fine-grained "facies" and the other a coarse-grained "facies" of the same rock. For geologists have come to employ "facies," with some disregard of its etymology, as meaning "variety" rather than "appearance." Acceptance of "microfacies" (and "megafacies") would thus almost obligate us to use the word "facies" in its neglected primary sense.

"Microfacial" and "microfacially" raise other questions. "Facial" is derived not from "facies" but from "face"; logically, if we are to have "microfacial" we should start with "microface." And, logic apart, I am afraid that "microfacial"—which might mean "having a tiny face"—is a bit ludicrous, and for that reason unlikely to survive. What need is there, anyway, of the adjective and adverb? "Microfacial characteristics" can only mean "microfacies." "Microfacially," in Mr. Brown's final example, could be replaced by "microscopically"—though "under the microscope" or "in thin section" would be more precise. There is little to choose between the last four expressions on the score of length,

[1] Published by permission of the Director, Geological Survey, U. S. Department of the Interior.

[2] ECON. GEOL. 38: 325, 1943.

and the triteness of the last three is perhaps offset by the fact that they are immediately understood. If "microfacies" ever becomes current, it too will be on the way to becoming trite.

"Microfacies" has nothing ludicrous about it; in fact it looks so much like a real word that one already seems to have met with it somewhere. Only trial could show, however, whether or not it would pay its way. And while it was on probation it would have to be defined by each user, not only because of its novelty but in order to avert the possibility of confusion suggested above.

FRANK C. CALKINS.

REVIEWS*

Micromeritics, The Technology of Fine Particles. By J. M. DALLA VALLE. Pp. xiv + 428; Figs. 100. Pitman Publishing Corp., New York and Chicago, 1943. Price, $8.50.

This text is entirely devoted to the subject of behavior and characteristics of small particles. As such it brings together a large mass of widely scattered material never before accumulated in one place. As an all-embracing term to designate the material covered in his book, the author has introduced a new name in the engineering field—*micromeritics,* the science of small particles.

Only particles which range in size from 10^{-1} to 10^{5} microns are considered. These include submicroscopic, microscopic and small macroscopic sizes, but not colloids. The completeness with which the author discusses the technology of fine particles is indicated by the following chapter headings: Dynamics of Small Particles; Shape and Size Distribution of Particles; Methods of Particle Size Measurement; Theory of Sieving and Grading of Materials; Characteristics of Packings; Electrical, Optical and Sonic Properties; Thermodynamics of Particles; Chemical Properties of Small Particles; Flow of Fluids Through Packings; Infiltration and Particle-moisture Relationships; Capillarity; Determination of Particle Surface; Muds and Slurries; Transport of Particles; Theory of Fine Grinding; Collection and Separation of Particulate Matter from Air; Atmospheric and Industrial Dust.

The text should be welcomed by workers in many fields, since practical applications of fine-particle technology are discussed which are of importance to soil physicists, mining and metallurgical engineers, chemical engineers, petroleum engineers, and geologists. A thirty-eight page selected bibliography forms a valuable supplement.

GEORGE SWITZER.

Years of This Land. By HERMANN R. MUELDER and DAVID M. DELO. Pp. xii + 243; Figs. 11; Pls. 11. D. Appleton-Century, New York, 1943. Price, $2.50.

Here is the story of the discovery, the conquest, and the development of the United States. It is not a "history text" for the authors do not

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

present an array of statesmen and generals, of dates and documents, but they attempt to relate our history to the soil, sand, grass, and trees and to the effect of the "whirling winds, the pressing rocks, the warming sun, the rushing waters." The dominant theme is the interrelation of history and geography. A country that is rapidly attaining middle-age must consider this interrelation "—if we are to avoid the increasing centralization of government in our state capitals." And on an international scale, "—we must learn to understand how isolation has become a dangerous policy now, because of the circumstances of history and geography." The interpretation of our nation's history in the light of geography and geology may thus be a good basis in planning our future.

The manner is stimulating, and the authors succeed in impressing the reader with a feeling of national pride brought about not by flag waving but by a logical understanding of the factors that have controlled and affected our nation's development. The reader feels, as did the early traveller, "—the exhilaration with which for the first time they emerged from the silent, gloomy grandeur of the forest into the gay, sunny profusion of a prairie." We may look back with interest at stories of the formation of new frontiers and the discoveries of Nature's hoard of minerals, but we must be aware that "the mineral frontier has disappeared in smelter smoke . . . the physical frontier of free or cheap land has likewise vanished. The future is still as elusive as fate, but the problems of the here and now and the perplexities of the past need not escape us."

Muelder is Professor of history at Knox College and Delo is in the geology department of that institution. The combination of historical lore with geographical consideration is unique and has resulted in a book that is entertaining and certainly thought-provoking. It should be read by every progressive American.

R. E. D.

Boom Copper. By ANGUS MURDOCH. Pp. 255; Pls. 15. The Macmillan Co., New Yrok, 1943. Price, $3.00.

Angus Murdoch has written a refreshing story of the history and development of the Lake Superior copper district. The book is far more than an interesting tale of a hoary American mining region, for it contains an accurate account of the history of the Keweenaw from the initial "rush" in 1843 to the present war. The authenticity of data indicates the vast library research the author must have undertaken. The lusty yarns exemplify the intimate association he had with upper Michigan oldtimers.

Introductory chapters delve into the ancient lore that has been unearthed regarding pre-Columbian and early American interest in the native metal that was long ago found along the shores of the greatest of the

Great Lakes. The exploratory work of Douglass Houghton is described as well as the political and social significance resulting from his report. The bulk of the book is made up of fascinating yarns of the early history of the region, but these include stories of the growth of the mining interests and the individuals—Ed. Hulbert, Quincy Adams Shaw, Alexander Agassiz, etc.—who developed the larger companies. The mining communities and the paternalism of Calumet and Hecla is described. The significance of the geology peculiar to the peninsula certainly has not been underestimated, and Murdoch's description of this is rather good. One chapter is devoted to a simplified consideration of Keweenaw geology, although the importance of geologic influence is to be noted throughout the book. Minor misconceptions are to be expected from a non-scientist author writing a book of this nature, but these errors are remarkably few. (He insists that conglomerate is a "flint-hard mineral.")

This is the first full book Mr. Murdoch has written, although he has written numerous travel booklets, and was Associate Editor of *The Plumbers Trade Journal*. Boom Copper is the only popular account of the Lake Michigan copper district and is a source of valuable information as well as abundant reader interest.

RALPH E. DIGMAN.

BOOKS RECEIVED.

RALPH E. DIGMAN.

Optical Crystallography. By ERNEST E. WAHLSTROM. Pp. 206; Figs. 208. John Wiley and Sons, New York, 1943. Price, $3.00.

Chronic Pulmonary Disease in South Wales Coalminers. II. Environmental Studies. Special Report Series, No. 244, Medical Research Council, His Majesty's Stationery Office, London, 1943. Price, 10s. 6d.

U. S. Geological Survey. Washington, 1942–1943.

Bull. 930–C. **Spirit Leveling in Illinois, 1896–1941...Part 3, East-central Illinois.** Pp. 362; Figs. 55; Pls. 4. Price, 40 cents.

Bull 935–C. **Tin Deposits of the Republic of Mexico.** WM. F. FOSHAG AND CARL FRIES, JR. Pp. 75; Figs. 2; Pls. 7. Price, 40 cents.

Bull. 936–N. **Antimony Deposits of the Stampede Creek Area, Kantishna District, Alaska.** DONALD E. WHITE. Pp. 15; Figs. 3; Pls. 2. Price, 25 cents.

Bull 940–A. **The Rose Creek Tungsten Mine, Pershing County, Nevada.** R. J. ROBERTS. Pp. 14; Fig. 1; Pls. 3. Price, 30 cents.

Prof. Pap. 197–C. **Lower Pennsylvanian Species of Mariopteris, Eremopteris diplothmema, and Aneimites from the Appalachian Region.** DAVID WHITE. Pp. iii + 54; Pls. 31. Price, 20 cents. *A posthumous work assembled and edited by Charles B. Read.*

Prof. Pap. 200. **Geology and Ore Deposits of the Magdalena Mining District, New Mexico.** G. F. LOUGHLIN AND A. H. KOSCHMANN. Pp. 167; Figs. 28; Pls. 38. Price, $2.00.

Prof. Pap. 202. **Geology and Ore Deposits of the Metaline Quadrangle, Washington.** C. F. PARK, JR., AND R. S. CANNON, JR. Pp. 78; Figs. 11; Pls. 34. Price, $1.50.

W. S. P. 888. **Stream-gaging Procedure. A Manual describing methods and Practices of the Geological Survey.** DON. M. CORBET AND OTHERS. Pp. xvi + 241; Figs. 14, Pls. 33; Tables 10. Price, 65 cents.

W. S. P. 916. **Summary of Records of Surface Waters of Upper Columbia River Basin in Montana and Idaho, 1898–1938.** A. H. TUTTLE AND T. R. NEWELL. Pp. 215. Price, 30 cents.

W. S. P. 921. **Surface Water Supply of the U. S. 1941. Part 1, North Atlantic Slope Basins.** GLENN L. PARKER AND OTHERS. Pp. 569; Pl. 1.

W. S. P. 925. **Surface Water Supply of the U. S., 1941. Part 5, Hudson Bay and Upper Mississippi River Basins.** GLENN L. PARKER AND OTHERS. Pp. 397; Pl. 1. Price, 45 cents.

W. S. P. 928. **Surface Water Supply of the U. S., 1941. Part 8, Western Gulf of Mexico Basins.** GLENN L. PARKER AND OTHERS. Pp. 309; Pl. 1. Price, 40 cents.

W. S. P. 936. **Water Levels and Artesian Pressure in Observation Wells in the U. S. in 1941. Part 1, Northeastern States.** O. E. MEINZER, L. K. WENZEL, AND OTHERS. Pp. 251; Figs. 11.

W. S. P. 937. **Water Levels and Artesian Pressure in Observation Wells in the U. S. in 1941. Part 2, Southeastern States.** O. E. MEINZER, L. K. WENZEL, ANL OTHERS. Pp. 119, Figs. 9.

W. S. P. 938. **Water Levels and Artesian Pressure in Observation Wells in the U. S. in 1941. Part 3, North-Central States.** O. E. MEINZER, L. K. WENZEL, AND OTHERS. Pp. 232; Figs. 5.

W. S. P. 939. **Water Levels and Artesian Pressure in Observation Wells in the U. S. in 1941. Part 4, South-Central States.** O. E. MEINZER, L. K. WENZEL, AND OTHERS. Pp. 178; Figs. 10.

U. S. Bureau of Mines. Washington, 1942–43.

Technical Papers.

647. **Production of Industrial Explosives in the United States.** W. W. ADAMS AND V. E. WRENN. Pp. 30. Price, 10 cents.

648. **Mineral Matter in Coal.** GEORGE C. SPRUNK AND H. J. O'DONNELL. Pp. 66; Figs. 48. Price, 15 cents.

649. **Carbonizing Properties and Petrographic Composition of No. 2-bed Coal from Bartoy Mine and No. 5-bed Coal from Wilkeson-Miller Mine, Wilkeson, Pierce County, Washington.** J. D. DAVIS AND OTHERS. Pp. 46; Figs. 29. Price, 10 cents.

651. **Coke-Oven Accidents in the United States. 1941.** W. W. ADAMS AND V. E. WRENN. Pp. 19; Figs. 3. Price, 10 cents.

653. **Explosion Hazards of Combustible Anesthetics.** G. W. JONES AND OTHERS. Pp. 47; Figs. 21. Price, 15 cents.

Bulletins.

451. **Syllabus of Clay Testing, Part 1.** T. A. KLINEFELTER AND OTHERS. Pp. 35; Figs. 12. Price, 15 cents.

452. **Quarry Accidents in the U. S. During 1941.** W. W. ADAMS AND V. E. WRENN. Pp. 89; Figs. 3. Price, 15 cents.

Canadian Department of Mines and Resources. Ottawa, 1942.

Geol. Surv. Pap. 42–11. **The Pinchi Lake Mercury Belt, British Columbia.** J. E. ARMSTRONG. Pp. 18; Fig. 1; Preliminary map. Price, 10 cents.

Geol. Surv. Pap. 42–14. **Preliminary Map. Gem Lake, Manitoba.** C. H. STOCKWELL. Price, 10 cents.

Province of Quebec, Dept. of Mines. Quebec, 1942–43

The Mining Industry of the Province of Quebec in 1942. VARIOUS AUTHORS. Pp. 103; Pls. 4.

Geol. Rept. 12. **Kitchigama Lake Area, Abitibi Territory.** W. W. LONGLEY. Pp. 34; Figs. 2; Pls. 7; Geologic Map in Color.

Geol. Rept. 13. **Flavrian Lake Area.** W. G. ROBINSON. Pp. 21; Geologic Map in Color.

Choctaw County Mineral Resources. F. E. VESTAL AND T. E. McCUTCHEON. Pp. 156; Figs. 18; Pls. 2. Mississippi Geol. Surv. Bull. 52. University, 1943.

Kansas Oil Field Brines and Their Magnesium Content. WALTER H. SCHOEWE. Pp. 35; Figs. 3. Kansas Geol. Surv. Bull. 47, Part 2. Lawrence, 1943.

Exploration for Oil and Gas in Western Kansas During 1942. WALTER A. VER WIEBE. Pp. 86; Figs. 30. Kansas Geol. Surv. Bull. 48. Lawrence, 1943.

The Occurrence and Production of Vanadium. GEORGE O. ARGALL, JR. Pp. 56; Figs. 10; Pl. 1. Colorado School of Mines, Quarterly. Vol. 38, Number 4. Golden, 1943. Price, $1.00. *A concise account of the geology and distribution of vanadium deposits in the world. In addition to descriptions of the mineralogy, prospecting and mining methods, the author describes methods of treatment, marketing and production figures.*

Oil and Gas Resources of Cass and Jackson Counties, Missouri. JOSEPH R. CLAIR. Pp. 208; Figs. 14; Pls. 7. Missouri Geol. Surv. Vol 27, Second Ser. Rolla, 1943. *A cloth-bound volume containing a thorough discussion of the stratigraphy, structural geology, and economic geology of this district in Missouri in their relations to the oil and gas occurrence. Several large structural maps and a columnar section are contained in the pocket.*

Geology of the Fire Clay Districts of East Central Missouri. H. S. McQUEEN AND PAUL G. HEROLD. Pp. 250; Figs. 6; Pls. 39. Missouri Geol. Surv. Vol. 28, Second Ser. Rolla, 1943. *Here the Assistant State Geologist of Missouri and the Professor of Ceramic Engineering at the state university have combined talent to write a description of the two important fire clay districts located in east central Missouri.*

The Coal Beds of Western Carroll County and the Coal Beds in Southeastern Mahoning County. RAYMOND E. LAMBORN. Pp. 33. Ohio Geol. Surv. Bull. 43, Fourth Series. Columbus, 1942.

SOCIETY OF ECONOMIC GEOLOGISTS

SEPTEMBER 1, 1943.

NOTICE OF NOMINATIONS FOR OFFICERS.

The Nominating Committee, consisting of K. C. Heald, Chairman, B. L. Miller, and A. B. Yates, presents the following nominations for office:

President for 1945	*First Vice-President for 1945*
OSCAR E. MEINZER	THOMAS B. NOLAN

Councilors for 1944–1946

H. A. BUEHLER — PAUL BILLINGSLEY — W. L. WHITEHEAD

Regional Vice-Presidents for 1944

ALEXANDER DUTOIT	For *Africa*
BALARAM SEN	For *Asia*
F. L. STILLWELL	For *Australia*
ALFRED BRAMMAL	For *Europe*
J. A. ALLAN	For *North America*
VICTOR LOPEZ	For *South America*

The list of nominees is subject to additions proposed by the membership at large, in accord with Section 16 of the By Laws, which states:

> "Any further nomination or nominations proposed and supported in writing by ten or more members shall, if received by the Secretary within seventy-five days, be added to the official ballot."

Any additional nominations in accord with the foregoing provisions will appear on the ballot as regular nominees. The period for additional nominations closes on November 15, 1943, and such nominations must be received by the Secretary before or on that date.

Attention of the membership is especially directed to the need for prompt action if substitute nominations are contemplated.

THIS NOTICE IS NOT A BALLOT.

CHAS. H. BEHRE, JR., *Secretary.*

DEPARTMENT OF GEOLOGY,
COLUMBIA UNIVERSITY,
NEW YORK CITY, U.S.A.

ANNUAL MEETING, FEBRUARY, 1944.

The Annual Meeting of the Society of Economic Geologists will be held at the Waldorf-Astoria Hotel, New York City, February 21–24, 1944. The Geological Society of America, with whose meetings the Society of Economic Geologists usually joins in alternate years, will not hold its scientific sessions in December 1943, because of the war. This fact prompted the Council of the Society of Economic Geologists to accept an invitation from the American Institute of Mining and Metallurgical Engineers for a joint meeting with the Committee on Mining Geology and the Industrial Minerals Division of the Institute, a procedure followed in alternate years but not normally scheduled for 1944.

The Program Committees of the three cooperating groups are planning six half-day sessions, of which two will be devoted to ore deposits, two to industrial minerals, one to ground water problems and engineering geology, and one to problems of interest to geologists generally. The details of this program will be announced in a later issue of ECONOMIC GEOLOGY.

The annual dinner of the Society will be held on the night of February 22. It will be the occasion of the Presidential Address and of the presentation of the Penrose Medal.

Geologists wishing to present papers at the sessions are requested to communicate at once with a member of the Program Committee or the Secretary of the Society. Because of the exigencies of the war, papers may be submitted for presentation by designated readers despite the prospective absence of the authors. The closing date for acceptance of papers will be December 1.

C. H. BEHRE, JR., J. E. LAMAR,
M. H. GIDEL, J. W. PEOPLES,
C. P. JENNEY, V. T. STRINGFIELD,
PAUL WEAVER,
Program Committee.

NOTICE OF MANPOWER QUESTIONNAIRES.

The officers of the Society take this means of bringing to the attention of faculties in geology in American colleges and universities the following matter.

The War Manpower Commission and the National Roster of Scientific and Specialized Personnel are engaged in appraising the number of geologists available at present and in the near future. A questionnaire has been prepared with the collaboration of the Committee on Personnel of the National Research Council, which has been sent to the Departments of Geology and Geophysics. The aim of the questionnaire is to determine for each institution the numbers of persons available as teachers, the type of instruction given, and the numbers of students of differing degrees of advancement trained during the past academic year; it is hoped thus to obtain a quantitative estimate of the status of geologic training in wartime.

The data requested may greatly affect the national policy toward geologists and geologic training during and immediately after the war. In any case, the results of this investigation should make an important contribution toward a clear overview of the position of geology in the United States today.

We solicit the hearty and prompt cooperation of the faculty members who are approached in this census.

WILLIAM B. HEROY,
President,
CHAS. H. BEHRE, JR.,
Secretary.

WALTER EDWARD McCOURT.

1884–1943.

Walter Edward McCourt, Assistant Chancellor and head of the Department of Geology and Geography of Washington University, died unexpectedly of a heart attack at his home in St. Louis on May 30. He is survived by his wife, Edna Wahlert, and his son Andrew, now in the Armed Forces.

Born in Brooklyn, New York, February 2, 1884, he received the degrees of Bachelor of Arts in 1904 and Master of Science in 1905, at Cornell University. Here he served as assistant in geology and in 1905–06 as an instructor. Dr. Heinrich Ries recalls his characteristic enthusiasm and energy, so inspiring to his students. In the summers of 1903–06 he was geologist for the New York State Agricultural Experiment Station, the New York Museum, and the New Jersey Geological Survey.

In 1906 McCourt began at Washington University a distinguished career as teacher of geology and university administration. He was promoted through successive ranks from instructor to professor and head of his department. He served at Washington University as dean of Schools of Engineering and Architecture during 1920–28, as dean of the College of Liberal Arts during 1930–32 and 1937–39, and as assistant chancellor from 1928 until his death. Through his energy and foresight, Newton R. Wilson Memorial Hall of Geology was built in 1924 and an excellent library, collections, and research equipment were developed.

Dean McCourt was a fellow of the Geological Society of America, the American Association for the Advancement of Science and chairman of its Section E in 1935, and a member of the Society of Economic Geologists, of Sigma Psi, and for the last 22 years of his life of the Engineers Club of St. Louis (president in 1929). For thirty-seven years he was an active member of the American Institute of Mining and Metalurgical Engineers; founding member of the St. Louis Section, he was for long its secretary-treasurer. From 1938 to 1941, he was a director of the Institute.

McCourt's summer field sessions of 1910–11 and '12 with the Missouri Bureau of Geology culminated in the publication of a comprehensive report on the Geology of Jackson County. He consistently encouraged the development of Missouri's mineral resources, serving the State Geological Survey, headed by his friend Dr. H. A. Buehler, as a member of the Board of Managers (1930–33). From 1913 to 1929 he taught geology and geography at the University of Colorado where he held the rank of professor. Ever conscious of the field as the true place for teaching geology, he pioneered the establishment of the geological laboratory at Science Lodge, near Boulder.

McCourt was an accomplished and stimulating lecturer, and sincerely loved to teach. To the end, despite increased administrative duties, he conducted the general elementary class in geology, a large factor in quickening the interest of many students in science and in geology, and reflecting McCourt's cultural appreciation of geology. Yet he fully realized the need for rigorous quantitative treatment of the subject in training specialists.

As teacher and administrator, Dean McCourt contributed incalculably to the great development of Washington University. His sincere and

forthright nature brought respect, affection, and a host of friends, within the University, in the community at large, and over the entire country.

CARL TOLMAN.

PAUL FREDERICK BOSWELL.

Paul Frederick Boswell, a native of South Carolina who combined in his person the charm of the Old South with the dauntless self-reliance and energy of the West, died in the Philippine Islands late in 1941. He acquired his early geological training under Stephen Taber at the University of South Carolina, but his restless spirit urged him to the more active life in the western states. At Stanford in his post-graduate work he specialized in physico-chemical applications under H. W. Morse; here his keenly analytical mind and outstanding personality at once found field for expression.

After finishing graduate study in 1922 he served for a time as metallurgist in a California steel plant. However, his nature craved the challenge which the mining industry of the West then afforded. During the next ten years he was active throughout the southwestern United States and northern Mexico in scouting and making detailed geological examinations of mines, for a time in managing a property, and in attacking the various metallurgical problems which arose in connection with his work. During this period he became associated with the Leached Outcrop investigation, to which he contributed so many fertile ideas and such sound procedure. He was brilliant in conception, extraordinarily capable in focussing upon fundamentals, and gifted in resolving the difficult into simple terms. His thorough grounding in physical chemistry proved to be the "catalyst" needed for achieving orderly progress in field classifications of the limonitic derivatives.

Shortly after this period ill health beset him, but he recovered sufficiently to participate in the Philippine gold boom of the middle 30s. However, the impediment never was fully overcome, and in the end cut short his career in midlife. He died at the age of forty-three. He is survived by his wife, Alice Bradley Boswell, and two children.

During his brief career he held membership in the American Institute of Mining and Metallurgical Engineers, the Society of Economic Geologists, the American Chemical Society, and the American Electrochemical Society. Though his written contributions were limited to those published in connection with the Leached Outcrop interpretations, he contributed freely and stimulatingly to discussion of every type in local sessions and council meetings. He made friends without effort, and his ideas were eagerly sought for their transparent clarity and respected for their basic soundness. Through these ideas transmitted verbally, and through his published contributions to the Leached Outcrop technique, he left his imprint indelibly upon economic geology.

ROLAND BLANCHARD.

July 16, 1943.

SCIENTIFIC NOTES AND NEWS

E. S. MOORE of the University of Toronto department of geology spent the summer with the Ontario Department of Mines preparing maps and reports on the Goulais River iron range, the Josephine property, and others in the Michipicoten district.

G. B. CRESSEY, chairman of the department of geography and geology, has leave of absence from the University of Syracuse to act as a representative of the U. S. Department of State in China.

FREEMAN WARD, professor of geology and head of the department at Lafayette College, died on September 14.

R. M. FOOSE of the Pennsylvania Geological Survey is in charge of all strategic mineral investigations in the state.

K. A. GORTON, formerly instructor in geology and mineralogy at Purdue University, is now geologist with the Potash Co. of America.

P. G. NUTTING retired from active duty with the U. S. Geological Survey on August 31. He has been engaged in physico-chemical studies of clays since 1925.

N. S. HINCHEY has accepted a position as assistant professor of geology at Washington University, St. Louis, Missouri.

J. O. FULLER, formerly instructor in geology at Ohio State University, has been appointed assistant professor of geology at the University of Virginia.

CHARLES GWYNNE, associate professor of geology at Iowa State College, spent part of the summer in survey work for the South Dakota Geological Survey.

J. F. ROMINGER, formerly with the geology department of Northwestern University, is now working on vanadium deposits for the U. S. Geological Survey.

L. M. PIDGEON, who developed a new process for the recovery of magnesium from dolomite, has been appointed head of the department of metallurgy at the University of Toronto.

B. H. PARKER of the Colorado School of Mines at Golden, has been elected vice-president in charge of geology and land work of the Frontier Refining Co.